# Analysis of the embodied and operational energy: Study of a suburban house in Athens, Greece

by

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## Acknowledgments

The purpose of this dissertation was to explore the field of embodied energy in construction materials in Greece. It was a very interesting research and I feel obliged to thank the people that helped me.

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## Abstract

Operational energy can establish how successful a building is, in terms of environmentally 'considerate' design. Though embodied energy of construction materials also comprises an important indicator of the environmental impact of the material, the construction industry does not really promote it as such. This report enhances the significance of embodied energy and its relationship to operational energy (energy in use). Since buildings are becoming less energy demanding, operational energy will be decreasing, so that embodied energy will be gaining ground in the attempt to protect the environment. By the use of an 'environmentally friendly' house as a case study, it was proven that, though changes of the wall, floor, and insulation materials can take place, the operational energy does not change. What is greatly affected is the embodied energy of these construction materials.

## Literature Review

This Report analyzed the embodied energy of the construction materials in a 'environmentally sustainable' suburban house in Athens, Greece. Embodied energy can be calculated by the use of a system called 'Life Cycle Assessment (LCA)'. The work of four research groups around Europe was used, in order to result in final energy figures. The IVAM Research and Consultancy on Sustainability Group have created a very important LCA database, data from which were used in this Report. Another institute that contributed its literature is the Construction Industry Research and Information Association (CIRIA). Important information was also taken by the work on Life Cycle Assessment of the British Research establishment (BRE), as well as the Danish Building Research Institute (DBRI).

The assumptions that were made, regarding climate change predictions in Greece, were taken by the significant work of the Institute of Environmental Research and Sustainable Development, which is part of the National Observatory of Athens. More specifically, the Report used, was called 'Climatic Changes in the Mediterranean' (Athens, 2001) and its future predictions regarding temperature and precipitation changes in Athens were a strong plinth to base the work of this Report.

## Introduction

The Kyoto Agreement, signed by the majority of the world's countries, emphasizes the importance of the reduction of energy dependent on fossil fuels and takes measures for this serious issue. Since the building sector is one of the most energy consuming in Greece, there is a need to decrease the energy involved in buildings. Apart from the energy used throughout the lifetime of a building, increasingly important has become the energy spent in the manufacturing of the construction materials, known as 'embodied energy'. Governments have been promoting the idea of more energy efficient building, but have not greatly encouraged the use of materials with low embodied energy. This Report will try to promote the significance of embodied energy of construction materials in the Greek housing sector. There will be an analysis and a comparison between energy use and embodied energy of a suburban house in Athens, Greece.

# Chapter 1. Introduction

## 1.1 Climatic and Weather data for Greece

Greece has a total area of 13,195,740 ha and is located at the southern part of the Balkan region. It is divided into 52 counties that in turn are grouped into 13 administrative regions. Greece is primarily a mountainous country. Agricultural land covers 30% of the total land, while urban areas, industrial areas and internal waterways represent only 8% of the total.[1]

Athens is the capital of Greece, located on the southern part of the mainland. It is a city surrounded by two large mountains and is adjacent to the sea on its southern end. The majority of the housing stock in the city is comprised by 4-5 storey-high blocks of flats, whereas the suburbs mostly include detached houses. The residence that will be tested in this Report is a suburban villa with a bioclimatic design approach, located on the north-east part of Athens, at the outskirts of mount Immitos.

In table 1, one can notice all the basic meteorogical information taken for the period 1931 to 1990. There are data for every month of the year about temperature, precipitation, humidity, pressure, cloudiness and sunshine duration. In general it can be said that Athens has a temperate climate, with mild winters and hot and dry summers.

[1] "2nd National Communication to the United Nations Framework Convention on Climate Change", National Observatory of Athens, Institute of Environmental Research and Sustainable Development, Athens, 1997.

| Climate Data | Meteorological station of the National Observatory of Athens (Lofos Nimfon, Thession) latitude 37° 58' B, longitude 23° 43' A, altitude 107 m above MSL) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Year | Time period |
| Mean ambient temperature (°C) | 9.3 | 9.9 | 11.3 | 15.3 | 20.0 | 24.6 | 27.6 | 27.4 | 23.5 | 19.0 | 14.7 | 11.0 | 17.8 | 1931 1960 |
| | 9.3 | 9.8 | 11.7 | 15.5 | 20.2 | 24.6 | 27.0 | 26.6 | 23.3 | 18.3 | 14.5 | 11.1 | 17.6 | 1961 1990 |
| Mean maximum ambient temperature (°C) | 12.9 | 13.9 | 15.5 | 20.2 | 25.0 | 29.9 | 33.2 | 33.1 | 29.0 | 23.8 | 18.7 | 14.6 | 22.5 | 1931 1960 |
| | 12.9 | 13.6 | 16.0 | 20.3 | 25.3 | 29.8 | 32.6 | 32.3 | 28.9 | 23.1 | 18.6 | 14.7 | 22.3 | 1961 1990 |
| Mean minimum ambient temperature (°C) | 6.4 | 6.7 | 7.8 | 11.3 | 15.9 | 20.0 | 22.8 | 22.8 | 19.3 | 15.4 | 11.7 | 8.2 | 14.0 | 1931 1960 |
| | 6.5 | 6.9 | 8.4 | 11.6 | 15.4 | 20.1 | 22.5 | 22.3 | 19.2 | 14.9 | 11.4 | 8.3 | 14.0 | 1961 1990 |
| Mean precipitation (mm) | 58.8 | 36.5 | 37.5 | 22.0 | 22.5 | 13.6 | 5.7 | 7.0 | 15.3 | 51.0 | 55.7 | 71.1 | 396.8 | 1931 1960 |
| | 44.6 | 48.3 | 42.6 | 28.2 | 17.2 | 9.7 | 4.2 | 4.6 | 11.9 | 47.7 | 50.6 | 66.6 | 376.1 | 1961 1990 |
| Average number of raining days | 17 | 12 | 12 | 10 | 9 | 5 | 2 | 3 | 4 | 9 | 13 | 16 | 112 | 1931 1960 |
| | 13 | 13 | 11 | 10 | 7 | 5 | 2 | 2 | 3 | 9 | 11 | 13 | 99 | 1961 1990 |
| Average relative humidity (%) | 74 | 70 | 67 | 63 | 59 | 53 | 47 | 47 | 56 | 67 | 73 | 75 | 63 | 1931 1960 |
| | 72 | 71 | 68 | 62 | 58 | 52 | 48 | 49 | 56 | 66 | 73 | 73 | 62 | 1961 1990 |

Table 1. Information on the weather of Athens for a period of 60 years (1931-1999).

## 1.2 Energy Generation in Greece

For the past decade the total energy supply in Greece has been continuously increasing, reaching a total of approximately 23.7 Mtoe in 1995. This general rapid increase, however, comes in contrast to the average annual growth rate for the first five years of the 90s. In these years the average annual growth was reduced to approximately 1.4% per year, compared to 3.3% in the 80s. The Public Power Corporation (PPC) made a significant decision, which was to reduce the energy's dependency from petroleum products and correspondingly, to increase energy generation by the use of indigenous brown coal (lignite). That is why the percentage of energy produced by petroleum has fallen from 72.5% in 1980 to 60% in 1995. The partial replacement of oil by lignite had a marked effect on the import dependency of energy, which dropped from 85.6% in 1980 to 78.1% in 1995.[2]

**ELECTRICITY GENERATION IN GREECE**

| Functional Unit: Gwh | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|---|
| **Total Gross Generation** | 41,551 | 42,555 | 43,507 | 46,332 | 49,86 | 53,843 | 53,704 | 54,608 | 58,478 |
| of which: | | | | | | | | | |
| Hydroelectric | 3,782 | 4,504 | 4,096 | 3,866 | 5,058 | 4,111 | 2,725 | 3,463 | 5,332 |
| Wind Power | 34 | 36 | 37 | 73 | 162 | 451 | 756 | 651 | 1,021 |
| Coal | 266 | 438 | 282 | 45 | 12 | 14 | 6 | 20 | 78 |
| Lignite | 28,431 | 28,859 | 30,347 | 32,397 | 32,369 | 34,299 | 35,425 | 34,546 | 35,091 |
| Petroleum Products | 8,86 | 8,534 | 8,299 | 8,078 | 8,157 | 8,885 | 8,477 | 8,633 | 8,722 |
| Natural Gas | 75 | 78 | 332 | 1,713 | 3,907 | 5,92 | 6,133 | 7,061 | 7,988 |
| Industrial Wastes | 103 | 106 | 114 | 160 | 195 | 163 | 182 | 234 | 246 |
| **Total Net Generation** | 38,379 | 39,285 | 40,158 | 42,757 | 46,021 | 49,863 | 49,73 | 50,608 | 54,344 |
| **Final Energy Consumption** | 34,087 | 35,562 | 37,074 | 39,315 | 40,879 | 43,151 | 44,535 | 46,564 | 48,734 |

Table 2. Showing the analytical elements for the energy generation in Greece (1995-2003)

2 "2nd National Communication to the United Nations Framework Convention on Climate Change", National Observatory of Athens, Institute of Environmental Research and Sustainable Development, Athens, 1997.

## 1.3 International framework and National Commitments on Climate change

### *1.3.1 Climate Change*

The industrial revolution has changed the world we live in, particularly due to the use of technology. With its advanced technologies, it also increased the need and consumption of energy throughout the World. The lifestyle that has been adopted for the past century has become more energy demanding than ever. Energy is used in buildings, industries and other sectors. This energy is produced by the burning of fossil fuels, which, during this process, release carbon dioxide to the earth's atmosphere. This substance, among others, has been considered responsible for the global warming phenomenon. The earth's atmosphere, a thin blanket of gases, protects the planet from the harshest of the sun's ultraviolet radiation. The atmosphere, by trapping the earth's 'warmth', keeps rivers and oceans from freezing. Carbon dioxide and water vapor are the most important gases in creating this insulating blanket, commonly known as 'greenhouse effect'. However, the increase of these gas emissions results to an enhanced heat-trapping capability of the earth's atmosphere. Clearly, if more heat is trapped, then the earth's temperature will rise[3]. This has led the world's scientists to establish a framework on climate change.

### *1.3.2 Kyoto Protocol (1997)*

Recognizing early on the need for an effective instrument to provide confidence in addressing the climate change challenge, the United Nations held a Convention on Climate Change in Rio de Janeiro (1992). The third Convention was held in Kyoto, in 1997 and this finalized the negotiations related to the establishment of such legal instrument, the Kyoto Protocol on Climate Change[4]. The Protocol provided a foundation, on which future action could be intensified. It established for the first time, legally binding targets for the reduction of greenhouse gas emissions and it also confirmed the capacity of the international community to cooperate in action to deal with a major global environmental problem.

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[3] http://www.solcomhouse.com/globalwarming.htm, [September 2005]

[4] "Greece, National Plan on the Reduction of Greenhouse Gas Emissions (2000-2010)", Institute of Environmental Research and Sustainable Development, National Observatory of Athens, Athens, March 2002

According to the Protocol, Greece is committed to limit its greenhouses gas emissions for the period 2008-2012 to +- 25%, compared to the base year (1990 for CO2, CH4, N2O and 1995 for F-gases). Greece ratified the Protocol in 2002 (Greek Law 3017/2002) and adopted a National Plan for achieving the above mentioned commitment, by a decision of the Council of Ministers.

### 1.4 Greenhouse Gas Emissions in Greece

The most significant gases that affect the earth's atmosphere and are responsible for the greenhouse effect are carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and the commonly known F-gases (HFC's, PFC's, and $SF_6$). The emissions of carbon dioxide comprise the majority of the total greenhouse gas emissions in Greece, (80.6% of the total emissions) in the year 2000. Furthermore, methane ($CH_4$) and $N_20$ were responsible for 7.9% and 8.2% correspondingly. Finally, the remaining 3.3% is due to F-gases (HFC's, PFC's and $SF_6$). The emissions of the three basic greenhouses gases had a 23% increase throughout the decade (1990-2000). Consequently, the commitment that the country had towards the Protocol has not been achieved, so far. The greenhouse gas emissions for the years 1990 to 1995 can be seen in the table below (table 3). Furthermore, Figure 1 shows the increase of the three most important gases, as measured in Greece.

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|
| **Carbon dioxide** | 10,423 | 9,446 | 10,582 | 12,711 | 13,026 | 13,623 |
| **Methane** | 0.206 | 0.185 | 0.205 | 0.244 | 0.256 | 0.264 |
| **Nitrous oxide** | 0.515 | 0.472 | 0.542 | 0.632 | 0.672 | 0.721 |
| **Carbon monoxide** | 32.468 | 30.160 | 35.205 | 39.537 | 41.924 | 42.547 |
| **Oxides of nitrogen** | 173.759 | 158.496 | 179.567 | 213.921 | 222.424 | 237.737 |
| **NMVOCs** | 27.104 | 24.645 | 27.922 | 32.261 | 33.522 | 33.234 |

Table 3. Showing the emissions of the basic greenhouse gases in Greece, from 1990 to 1995

The current Greek Government has published a new Plan, which is formally known as the "National Plan on the Reduction of Greenhouse Gas Emissions (2000-2010)". Summarizing this Action Plan, it can be said that the energy sector is responsible for 76% of the total greenhouse gas emissions. Thus, the plan is related to the promotion of more renewable ways of energy generation, such as wind power, solar power, hydroelectric etc. More over, there were measures announced, concerning the energy consumed in the housing sector. Some of them were:

Improvement of thermal performance of the housing building sector:

- maintenance/replacement of central heating boilers
- shading devices, roof ventilators, night cooling
- use of more efficient air-conditioning systems
- use of energy efficient lamps
- Photovoltaics/ solar water collectors etc.

The embodied energy of construction materials was never mentioned in this Action Plan. This Report takes advantage of the Plan's omission and tries to promote the idea of the use of more renewable and less energy consuming construction materials.

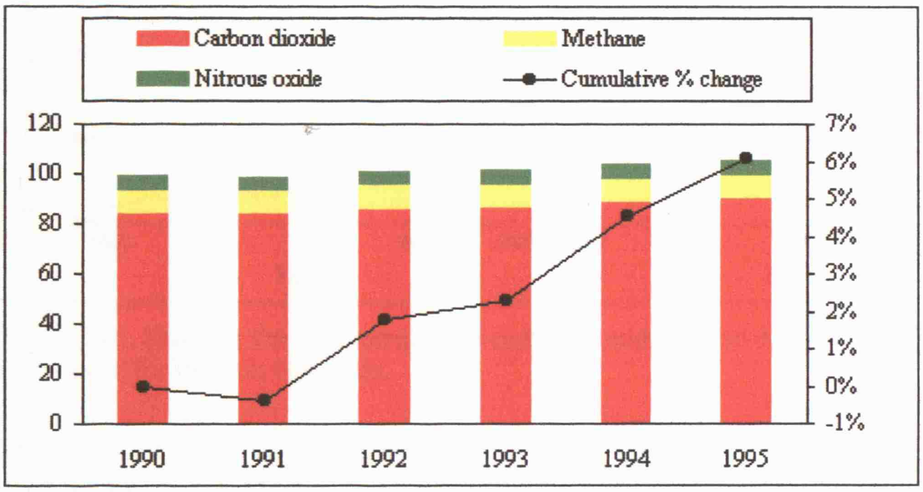


Figure 1. Showing the increase of greenhouses gas emissions for Greece (1990-95).

### 1.5 Climate Change Predictions in Greece

With the Industrial Revolution of the 18th century, man caused a rapid increase of the two most important greenhouse gases: carbon dioxide (CO2) and methane (CH4). The levels of this increase were unprecedented and continue to rise until today (figure 2 &3). As a result, the global surface temperature increased, lying between 0.4 to 0.8 degrees Celsius. Most of the increase has occurred in two distinct periods: 1910-1945 and 1976 to today[5]. The warmth of the 20th century appears to have had a naturally-forced component.

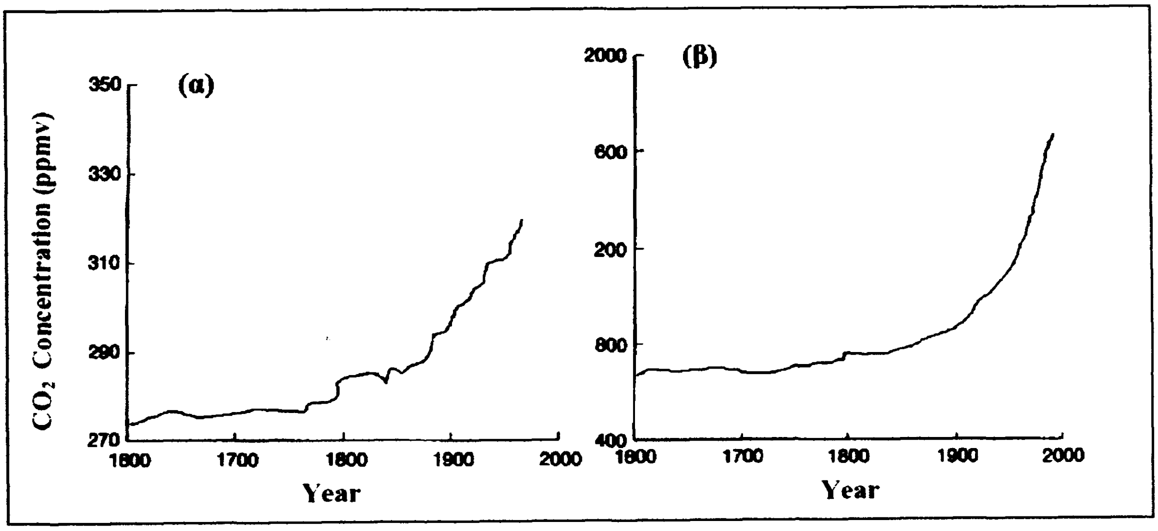


Figure 2&3. Showing the concentration of carbon dioxide (a) and methane (b) in the earth's atmosphere for the past 400 years.

However, the rate of warming of the 20th century appears to be too large to be explained by natural influences alone. Warming since the 1970's has been particularly rapid with all eight of the warmest years on record occurring since 1983. 1990's are likely to be the warmest decade of the whole millennium[6]. According to the scenarios presented to the Intergovernmental Panel on Climate Change (IPCC), this unprecedented rise of the greenhouse gas emissions will possibly lead to an increase of the global surface temperature between 1.7 to 4.0 degrees Celsius, until the year 2100 (figure 4).

[5] "Climatic Changes in the Mediterranean", Institute of Environmental Research and Sustainable Development, National Observatory of Athens, Athens, 2001
[6] "Climatic Changes in the Mediterranean", Institute of Environmental Research and Sustainable Development, National Observatory of Athens, Athens, 2001

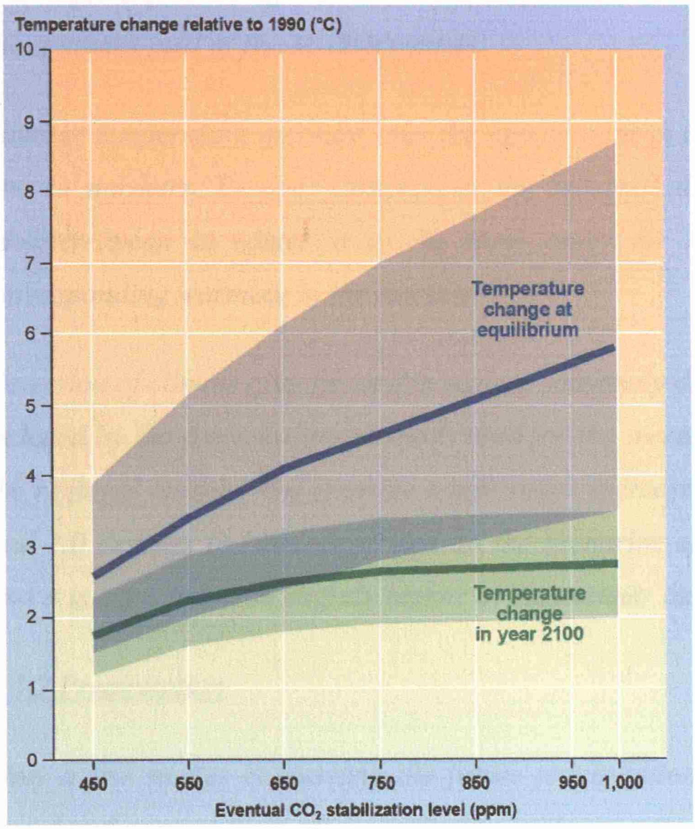


Figure 4. Temperature change predictions of the Intergovernmental Panel for Climate Change.

The research team of the *Institute of Environmental Research and Sustainable Development* (which is a part of the National Observatory of Athens) published a Report, which examined the validity of the previous assumptions, by drawing on the results of recent studies and reports and reviewing possible future changes in the climate, for the region of Greece in particular. The following data were part of their Report:

### 1.5.1 Temperature

*Temperatures over the Mediterranean may increase to as high as 3.5 degrees Celsius by the year 2050, assuming doubling of carbon dioxide concentration. The estimation of warming range over the Mediterranean presents a considerably high variation (2.0 to 6.0 degrees Celsius by the year 2100). A lower temperature increase is expected over the sea and the coastal regions compared to the inland Mediterranean areas.*

*The regions presenting the maximum temperature increase and sensibility are over the southern part of the Mediterranean.*

*Summer temperature increase over the Mediterranean is substantially higher than the one in northern Europe. Concerning the seasonal differences, warming over the Mediterranean in winter is of the same order (or it is slightly lower) with the corresponding warming in the summer.*

*Detection of climate change on this scale is extremely difficult due to the uncertainties induced by the downscaling methods used for the increase of the coarse resolution of the regional models. The average temperature increase over Greece lies between 0.9 and 2.0 degrees Celsius, depended on the scenarios of greenhouse gases reduction, and it is expected to be slightly higher in the summer (as far as 0.5 degrees Celsius).*

### *1.5.2 Precipitation*

*Only a few studies concerning the future precipitation regime in Greece have been found and most of them offer conflicting evidence over how precipitation may change over the area. There are serious indications, however, for a remarkable decline in summer precipitation, which is consistent with the projections over the Mediterranean region as a whole. It should be mentioned that, according to the simulation results of one study, east and south Greece, and especially Attica, Thessaly, Thessaloniki and eastern Peloponnesus are likely to experience the larger decrease in mean annual precipitation in the northern part of the Mediterranean region. However, the Greenpeace technical report for the climate change in Crete suggests that the mean annual precipitation will rise from 14.3 to 23.8 mm by the year 2030 (table 5).*

After a description of how the climate in Greece might become, follows a different subject, which involves energy consumed by the building sector. The following chapter will try to describe the different types of energy that are found in a building.

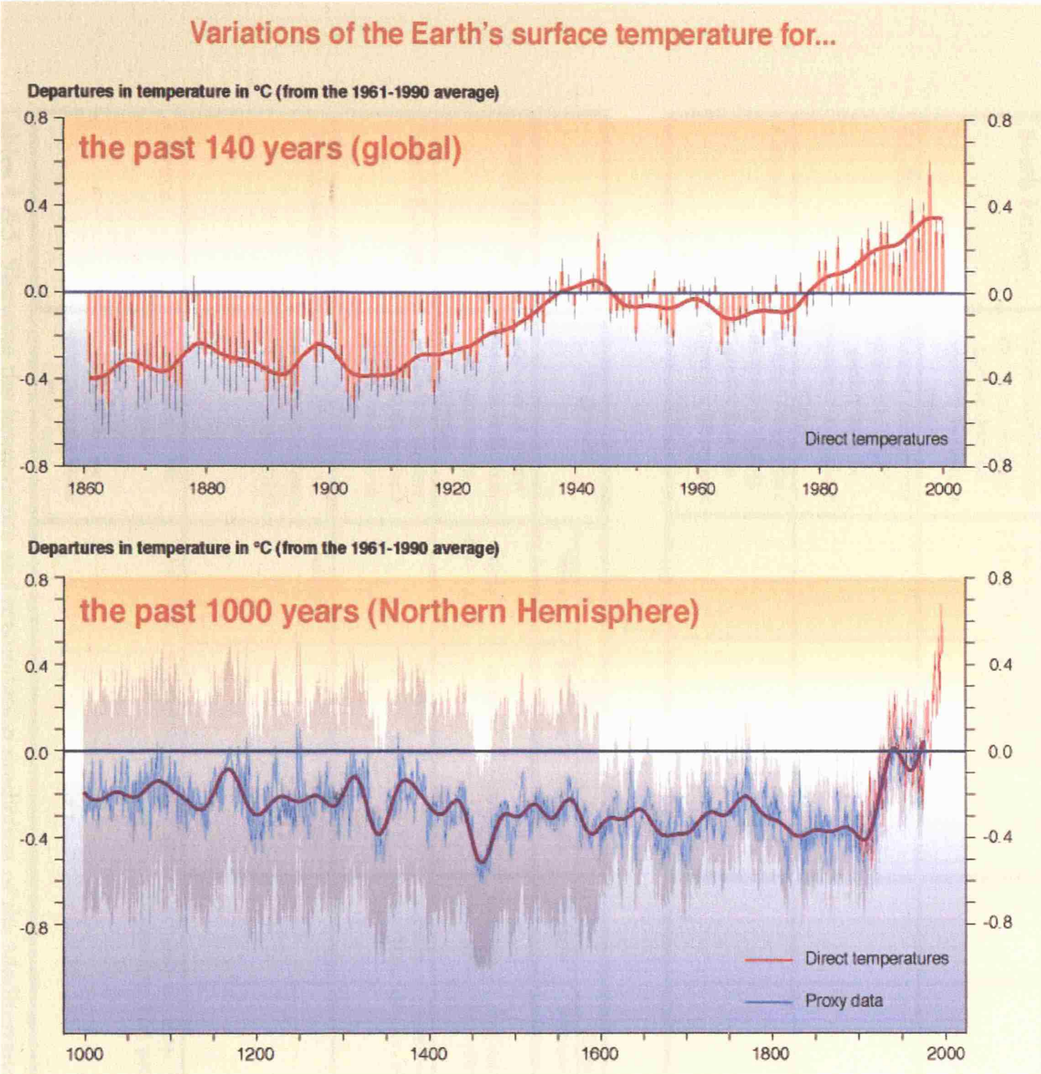


Figure 5 & 6. Showing the temperature variations for the past149 and 1000 years, correspondingly.

| | In general | 2030 | | | 2050 | | | 2100 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Winter | Summer | Annually | Winter | Summer | Annually | Winter | Summer | Annually |
| **North Europe** | Winter temperature increase is greater than the respective increase in summer | increase 2.5 to 4°C | increase 1 to 3°C | | | | | increase 4 to 7°C | increase 2 to 5°C | |
| **South Europe** | Summer temperature increase is slightly greater than the respective increase in winter | increase 1.5 to 3.5°C | increase 2 to 4.5°C | | | | | | | |
| **Mediterranean** | Summer temperature increase is slightly greater than the respective increase in winter | | | | | | increase 3.5°C | increase 4 to 5°C | increase 4 to 7°C | increase 4 to 6°C or 2.5 to 5°C |
| **Greece** | Summer temperature increase is slightly greater than the respective increase in winter | | | increase 0.9 to 2°C | | | | | | increase 2 to 2.5°C |

| | In general | 2030 | | | 2050 | | | 2100 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Winter | Summer | Annually | Winter | Summer | Annually | Winter | Summer | Annually |
| **North Europe** | Increase in winter and some indications for increase in summer | increase 0 to 20% | increase | increase | increase 0 to 20% | Increase 0 to 20% | increase | increase 0 to 30% | change -20% to 10% | increase . |
| **South Europe** | Decrease in summer and indications for a slightly increase in winter | | decrease | | increase 0 to 10% | decrease -5% to -15% | | increase | decrease | |
| **Mediterranean** | Great decrease in summer and increase in winter to the north | decrease | | decrease -10% | | | | increase 0 to 20% in particular to the north | decrease 0 to -40% | increase to the north, decrease -10 to -40% to the south |
| **Greece** | Decrease of the summer precipitation. Indications for increase in northern Greece only. | Only few studies concerning the future precipitation regime in Greece have been found and most of them offer conflicting evidence over how precipitation may change | | | | | | | | |

Tables 4 &5. Showing the temperature and precipitation prediction of the Mediterranean Region.

# Chapter 2. Background on Energy

## 2.1 Embodied Energy

In the process of the construction of a building, a complex combination of many materials is used. From the acquisition of natural resources to the delivery of the material to the construction site, a significant amount of energy is consumed. This is known as "embodied energy" of the construction materials. In Greece, building occupants usually follow the aesthetic trends of the time for their homes and forget the fact that, for example, the timber used in their homes has been transported from places like southern Africa of Brazil. The energy spent for the transportation of a material is very important and increases significantly its embodied energy.

A typical construction material, extensively used in Greece, is concrete. Due to the intense frequency of earthquakes in the area, concrete frames are considered to be the best solution for Greek buildings. Typically, the process of producing concrete can be described by the following:

- extraction of cement as a raw material from quarries
- transportation of cement to the factory
- burning process to produce the cement
- extraction of aggregates from quarries
- transportation to the manufacturer
- crashing of aggregates
- transportation of cement to the concrete production factory
- transportation of aggregates to the concrete production factory
- mixing of cement, aggregates and water
- transportation of concrete onsite

One can realize the amount of energy consumed throughout the process explained above. The petrol used for transport and the electricity for the other activities makes concrete a material with quite a high embodied energy.

On the other hand, the site can be full of stone, which can be used if not for the construction of the building, then at least for cladding external walls and landscaping.

In this case, no transportation or manufacturing of the stone would be involved. Thus, natural materials found onsite have generally the lowest embodied energy.

### *2.1.1 Recurring Embodied Energy*

'Recurring embodied energy represents the non-renewable energy consumed to maintain, repair, restore, refurbish or replace materials components or systems, during the life of the building'[1].

Recurring embodied energy is very difficult to estimate over the long term, since the non-renewable energy contents of replacement materials, components or systems are difficult to predict. For example, how energy intensive will glass be in 100 years. As the technology evolves, the process of glass manufacturing is constantly changing. This is quite well known, due to the debate between environmentalists and glass manufacturers about the energy consumed in double glazing manufacturing. However, as buildings become more energy efficient and the amount of operating energy decreases, embodied energy becomes a more important consideration.

## 2.2 Energy in use (Operational Energy)

It is common sense that throughout the lifetime of a building, energy is consumed by its occupants. This energy is mostly spent in space and water heating, space cooling, electrical appliances and lighting. This is called 'energy in use' or 'operational energy'. For the past few decades, an effort has been made in reducing the energy consumed in buildings. It is significant to mention that around 65% of the net energy produced in Greece is spent in residential and commercial buildings.[2] This shows the imperative need to reduce the energy demand through more energy efficient buildings.

The reduction of energy consumed in buildings does not only contribute to the decrease of CO2 emissions to the environment, which means prevention of global warming. It can also benefit the occupants by having a lower cost and a better,

[1] http/www.cdarchitect.com [June 2005]
[2] "Energy Balance in Greece (1995-2003)", Ministry of Development of Greece, Athens, 2003.

healthier lifestyle. The initial capital cost of an energy efficient house can be higher than that of a conventional house, but the payback time is short and after that, the occupant enjoys the benefits of energy consumption reduction. Furthermore, buildings that show respect to the environment have been produced by healthier, non-toxic materials and can allow a healthier living for the occupants.

A lot of effort has been put in the promotion of passive solar systems in buildings such as high thermal mass materials, high levels of insulation, the use of double glazing, sunspaces, Trombe walls etc. Furthermore, the advanced technology has allowed the use of active solar systems even in residential buildings. For the past few decades occupants are more and keener in using solar water collectors, photovoltaic panels, wind turbines, heat recovery systems and many other devices that contribute to the reduction of building energy consumption.

By the use of computer software, an estimate of the annual heating and cooling load of a building can be calculated. In this Report, the program called TAS (Thermal Analysis Simulation) has been used in calculating these numbers.

## 2.3 The relationship between "embodied energy" and "energy in use"

In order to make sensible decisions about buildings in general - and residential buildings in particular - and energy efficiency, it is significant to understand the relationship between 'embodied energy' and 'energy in use'.

The Report "Sustainable Homes: Embodied Energy in Residential Property Development" by Crane environmental Limited will be used to explain this relationship. A new-build three-bedroom house in the UK has a certain amount of embodied energy. This would be overtaken by the "energy in use" within the first 2 to 5 years of its lifetime[3]. After this period, the energy use would continue to rise, as it can be observed in figure 1. If it is assumed that the house would have a lifetime of 60 years, then throughout his lifetime, the energy use will be 12-30 times the embodied energy.

[3] "Sustainable Homes: Embodied Energy in residential Property Development", Sustainable Homes Project, Report by Crane Environmental Limited, 1999.

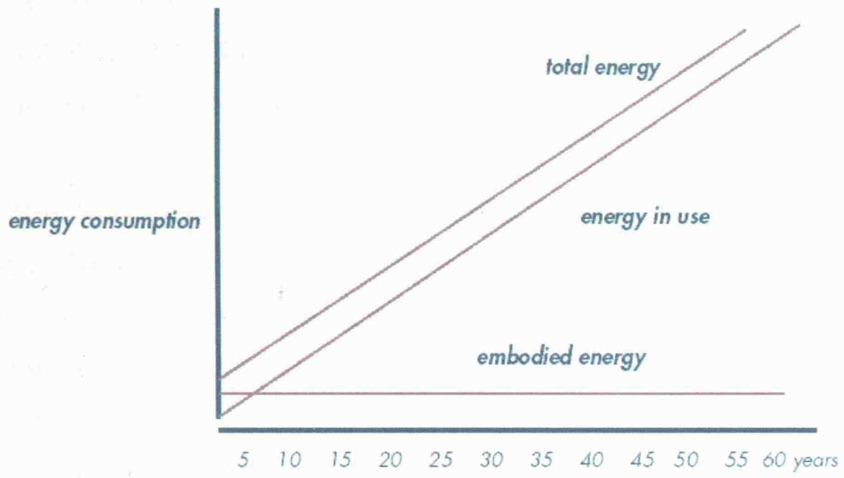


Figure 1. Graph showing the energy use and the embodied energy of a three-bedroom house in the UK.

As it can be seen on the graph, energy use will 'overtake' the energy use in maximum five year's time. Furthermore, within the 60 year's lifetime, embodied energy accounts for only about 10% of the energy use of the building. These results can lead us to a logical conclusion: however much embodied energy is saved in a building, it will never be as significant as the saving of energy used by the building during its lifetime.

There is also the case of existing energy efficient homes, also known as "zero energy" homes. In this case, energy in use will never become as important as the embodied energy of the building. However, even if the embodied energy was doubled, the total energy consumed during the lifetime of the house would still be greatly reduced[4]. The initial embodied energy input would be recovered many times over.

There is though, an important factor that needs to be considered. This is the fact that buildings are becoming more and more energy efficient. The whole campaign about global warming and the need to be more energy efficient in our lives, has started to be more effective to the people. Environmental awareness is being raised more and more and governments have placed the "environment" on the top of their agendas. More over, technology has improved and has contributed to the reduction of the amount of

[4] "Sustainable Homes: Embodied Energy in residential Property Development", Sustainable Homes Project, Report by Crane Environmental Limited, 1999

energy consumed in a building. For example, gas combi-condensing boilers are contributing in the decrease of energy use in homes[5]. All these have resulted in the overall reduction of energy in use.

Furthermore, more energy efficient buildings means materials with higher embodied energy are used (such as thermal insulation, larger amounts of thermal mass used in walls and floors, double glazing etc). It also means the use of advanced technologies in homes (such as solar collectors, photovoltaics, wind turbines etc), which consume a significant amount of energy during their production (embodied energy). All the above have resulted in the reduction of energy use and the increase of embodied energy. This means that the significance of embodied energy compared to energy use is becoming more intense.

As it can be concluded, it is still worth reducing embodied energy, but without compromising the overall performance of the building. For example, thermal insulation is usually a manufactured product, high in embodied energy. This does not mean that the architect should prefer a smaller amount of thermal insulation to be placed on the skin of the building. Insulation should remain as high as possible, because this will lead in great saving of annual energy spent within the building.

In Greece, there is also the issue of earthquakes. The last earthquake in the capital of Greece, Athens, killed around 100 people. Most of them lost their lives due to the insufficiently strong structure of the building in which they were trapped. And, of course this is why the Greek Building Regulations insist on the use of reinforced concrete on building structures. As mentioned earlier, concrete is an extremely energy consuming construction material, but in this case, it cannot be avoided. What could be done is to promote the recycling of concrete, but this is a different issue altogether, which would require an analytical report on its own.

The next chapter will focus on the method used by scientists, in order to quantify the embodied energy of materials.

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[5] T. Oreszczyn, M. Gillott. "Energy efficiency beyond Part L." Architect's Journal (01/1995): Pages 39-41.

# Chapter 3. Background on Life Cycle Assessment (LCA)

### 3.1 Methodologies of Life Cycle Assessment (LCA)

It is interesting that, though the energy used in operating a building can be readily measured, the embodied energy contained in the structure is often hidden and can only be fully quantified, and thus appreciated, through a complete Life Cycle Assessment (LCA). In Europe there are several different research groups that have introduced methods of calculating embodied energy of building construction materials. Some of them are:

- Danish Building Research Institute (DBRI)
- British Research Establishment (BRE)
- Construction Industry Research and Information Association (CIRIA)
- IVAM Research and Consultancy on Sustainability

It does not make a great difference in which method can be used. The important thing is to remember that all the information collected will be based on primary energy and not delivered energy. Primary energy is the gross energy produced in power stations whereas delivered energy is the energy that is delivered to the end-user. This means that all the losses are not included and the delivered is the net energy. So, for example, in the case of concrete production, the electricity consumed by the factory should not be the one written on the monthly bill, but all the losses in the power generation station should be added.

An important element in the process of understanding the Life Cycle Assessment is that different materials can give a completely different result, if calculated for a different geographical area. An interesting example can make this observation clearer: Timber is considered to be a material with a low embodied energy. If a house is built in Greece and timber from South Africa is selected by the designer (though Greece produces its own timber), then the material becomes energy consuming. In this case, timber is not low in embodied energy, since, for example, a lot of petrol is wasted for the transport of the product to Greece.

And this shows the basic reason why vernacular architecture has always been successful. It is due to the use of local materials. In the old days, people did not have the option of importing materials from other countries, not even from other parts of the same country. Local designers used local materials, for example the stone found within the site was used to construct the walls of the building. And this makes vernacular architecture much closer to the idea of 'sustainable' design.

As a general rule it can be said that materials which are closer to their natural state, are potentially low in embodied energy. Materials that are manufactured and have gone through an industrial process (e.g. steel, aluminum etc) have, predominantly, high embodied energy.

In understanding the possibilities of environmental protection, the potential problems behind the embodied energy of materials should be explained. Starting from raw materials, the dangers in the ecosystem are due to the process that has been selected to collect the material. In many cases, there is a process of excavation and quarrying. A typical example is with aggregates used in the concrete. Especially in Greece, huge parts of mountains have been "eaten" away, in order to collect the valuable stone. Then this stone needs to be crushed, so that it can have the right thickness to be mixed with cement and, eventually, produce concrete. The excavation can potentially destroy natural habitats and create an imbalance to the ecosystem. The crushing process is quite energy consuming, so that the atmosphere is being aggravated with greenhouse gas emissions[1].

Another great problem that increases the embodied energy of construction materials is the transportation. Transportation means the use of vehicles, mostly lorries and ships. These vehicles use a great amount of petrol and, as a result, more carbon dioxide (and other greenhouse gases) is released to the environment, enhancing the global warming problem. Furthermore, any kind of industrial process can not only release $CO_2$, but also other chemical substances that can be harmful to human health. A good example is the adhesives that are used in the window making and in the glazing industry. The following sub-chapters will briefly explain the work of the four LCA research groups that were previously mentioned.

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[1] Website of the Intergovernmental Panel on Climate Change (IPCC): <http://www.ipcc.ch/ > [August 2005]

### 3.2 Danish building research institute (DBRI)

The Danish building research institute was involved in a research which compared timber and concrete framed buildings. This led to an extensive and analytical LCA of construction materials. Some assumptions, acceptances and restrictions were found in this complex process. The most interesting ones are described below[2]:

- the assessment was limited to outer wall, inner wall and flooring materials. Things like kitchen fittings were not calculated in this report.
- the service life was fixed at 50 years for all the materials involved
- the inventory analysis used mass balances to calculate the amount of used materials and the CO2 and other emissions related to these materials.
- In the methodology of the DBRI, the environmental impact of the materials is assessed. These are, for example CO2 on global warming, SO2 and NOx on acidification.
- The service includes all technical aspects, but does not include social and economic aspects

An interesting point that was realized in this report is that in Denmark steel is recovered from demolished buildings and clay bricks and concrete are crushed and re-used. This is quite impressive, since there is no such program in Greece. Unfortunately, most of the materials from demolished buildings are considered to be waste. Another unfortunate truth, another lost opportunity.

Finally the research concluded that the wooden building "contained" more embodied energy in its materials rather than the concrete panel building. The most significant outcome of the analysis is the correspondence of embodied energy to each material used in the building's main structure. Suggestively, some of the most common materials can be seen in the tables below.

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[2] Applications for environmental data and declarations for building materials. Hansen K., Grogh H., Danish Building Research Institute, 1998

| Floorings | Mass | Energy | CO2 |
|---|---|---|---|
| Total for concrete floorings | 310 kgr | 540 MJ | 61 kgr |
| Cement | | 41% | 62% |
| Steel | 41 kgr | 15% | 10% |
| Sand and stone | 4 kgr | 5% | 3% |
| Production | 246 kgr | 38% | 24% |

Table 1. Showing the inventory data for the concrete building as consumption of energy and emissions of CO2 divided into materials.

| Floorings | Mass | Energy | CO2 |
|---|---|---|---|
| Total for wooden floorings | 67 kgr | 520 MJ | 23 kgr |
| Wood products | 34 kgr | 44% | 18% |
| Gypsum | 24 kgr | 23% | 28% |
| Galvanized steel | 3 kgr | 18% | 31% |
| Mineral Fibres | 6 kgr | 16% | 22% |

Table 2. Showing the inventory data for the wooden building as consumption of energy and emissions of CO2 divided into materials.

### 3.3 British Research Establishment (BRE)

Statistics have shown that in the UK, around 30% of the energy consumed by the industrial sector involves the manufacture and transport of building materials. This is approximately 10% of the total annual energy consumption in the country[3].

In an effort to raise the awareness of construction professionals for the environment issues involved in the specification of building materials, the British Research Establishment followed its own path in analyzing and calculating embodied energy. The purpose of this research was to produce a guide for designers that would be easy to use and that would promote 'best practice' in minimizing the environmental impact

[3] "Biceps Module: Facilities Energy management", British Research Establishment, London, 1997

of building materials. The outcome was 'The Green Guide to Specification', an 'easy to use' guide that utilizes an A-B-C rating.

In a closer look, the BRE research team tried to arrange building materials and components on an elemental basis: external wall construction, internal walls, floors, finishes etc. This was a good decision, since the designers/green-guide users could compare and select from comparable systems or materials during the specification stage of the building. Although the process of environmental rating in the 'Green Guide' involved extensive quantitative data, these were not presented to the people that would use the handbook. Such an action would result in the frustration of the end-users, due to the complexity of calculating the mass of individual materials used in the construction of a building.

### *3.3.1 BRE Life Cycle Assessment*

The basic technique that research groups use to evaluate the environmental impact of construction materials is the Life Cycle Assessment (LCA). The BRE research team does not comprise an exception. This technique considers the full life cycle of the product, starting from manufacture/production, continuing to transport and utilization on the building and ending at the final stage, either treating the material as waste or recycling it.

The manufacture and use of a brick wall can be taken as an example of the process that the BRE Research closely followed:

- the clay is extracted and transported to the brickworks
- ancillary materials are transported and manufactured
- natural gas is extracted and distributed to be used for the brick kiln
- fuels are extracted from the earth and transported to power station to generate electricity
- raw materials used for the packaging are produced and transported
- bricks are manufactured in the brickworks
- bricks are transported to the site
- sand is extracted and mortar is produced and transported to the site

- the brick wall is built
- the wall maintenance involves painting or re-pointing
- the wall is demolished
- the materials are recycled or dumped

It is very important in the Life Cycle Assessment process to define a 'functional unit'. This would allow clarity in the comparison of different construction elements such as external walls, internal walls, floors etc. It would not be useful to compare, for example, mass of concrete and mass of steel for the structure of a building. This would not give as meaningful results, since the mass of steel used in such a case would be much less than the mass of concrete. Thus, the BRE team introduced the square metre as a functional unit, for a 60-year building life.

However, in this report, the mass or volume of materials will be used, since we do not compare building elements, but we calculate the energy of a single Greek house.

| Building material | Functional Unit | Embodied Energy (GJ) |
|---|---|---|
| Aerated concrete block | 1 tonne | 3.5 |
| Dense concrete block | 1 tonne | 0.61 |
| Clay tiles | 1 tonne | 6.8 |
| Granulated furnace slag | 1 tonne | 1.6 |
| Kiln dried timber | 1 tonne | 5 |
| Glass wool insulation | 1 tonne | 31 |
| Rockwool insulation | 1 tonne | 18 |
| Expanded polystyrene insulation | 1m2 (20kgr/m3) | 0.15 |
| Concrete (structural) | 1 tonne | - |
| Steel (for concrete reinforcement) | 1 tonne | - |
| Plaster | 1 m2 | - |

Table 3. Showing the basic materials used in buildings and their embodied energy, according to the corresponding functional unit. These are calculated for a 60 year life cycle.

## 3.4 Construction Industry Research and Information Association (CIRIA)

The Construction Industry Research and Information Association (CIRIA) has significantly contributed the data collection on "Life Cycle Assessment" of building materials. Their analysis took place at a time when there was an increasing interest in environmental issues, as far as the building industry is concerned. This association recognized the fact that there are limitations such as the complexity of the life cycles associated with the winning, manufacture, use and disposal of such materials. This is why it is believed that such a research is less than complete and that analytical techniques are still being developed. The other limitation is, of course, the balancing between environmental, social, health and economic issues. An interesting point that the CIRIA group has made in the Report is that:

Finally, it is worth mentioning that their report was a compilation of available information, numerous, often independent, sources rather than the results of a rigorous life cycle assessment of the materials concerned.

### *3.4.1 Life Cycle Assessment and Material Categories*

Life Cycle assessment is a technique that has been introduced in order to evaluate the environmental burdens associated to a product, a process or an activity. In the LCA process, an inventory is produced, within which all the materials are included in terms of their environmental impact. The CIRIA Report followed a distinction between five different categories:

- minerals (aggregates, cement, stone, gypsum, glass etc)
- metals (steel, aluminium, copper etc)
- plastics (thermoplastics used for insulation such as PVC's, polystyrene etc)
- timber (including hardwood, softwood, chipboard, cork, paper etc)
- paints, coatings, sealants and adhesives

Since this Report only focuses on the embodied energy of construction materials, the category that includes paints, coatings, sealants and adhesives will not be analyzed. A short analysis of all the other categories is, though, required.

*Minerals*

The minerals that were studied for Construction Industry Research and Information Association (CIRIA) are:

- aggregates
- natural stone
- clay products
- cement, substitutes and sub-mixtures
- gypsum/gypsum board
- mass concrete/in-situ concrete
- glass
- fill
- asphalt

The most common problem faced by the use of minerals is the surface extraction. All these materials are being extracted from the surface of the earth, leaving behind large gaps in the landscape (for example in the case of aggregates, in Greece we have noticed large parts of mountains are being left void). The noise and vibration from the extraction or crashing procedure is another environmental issue. The noise can be intolerable if it happens near residential areas, and it can also destroy natural habitats, by forcing animals to abandon their homes. There are also impacts on the flora, the surface and the groundwater. Finally, the visual impact of such a process, though subjective, is still considered to be an issue.

The Construction Industry Research and Information Association (CIRIA) has published some information about the most common materials and their embodied energy. They can be found in the table below:

| Material | Energy / mass (GJ/tonne) |
|---|---|
| Brick | 2.75 |
| Wet kiln concrete[4] | 6.4 |
| Dry kiln concrete | 3.8 |
| Plaster | 1.16-7.20 |
| Aerated concrete blocks (density 400kgr/m3) | 2.5 |
| Glass | 8.4-29 |
| Glass fibre insulation | 18 |

Table 4. A list of the most common minerals used in the construction industry, as published by CIRIA.

*Metals*

The metals mostly used in the construction industry are:

- steel and stainless steel
- copper and brass
- aluminium
- lead and zinc

Metals are frequently found in the construction procedure. There are different parts of the process that metal components can be used. In Greece, the most common use of steel is for reinforcing concrete structures. Not so frequently, they are seen in steel frame structures or as metal claddings (for example cladding panels, tubes ducts etc). Finally, many window frames and window shutters are made of aluminium, which is quite energy demanding and also contributes to overheating problems of buildings in the summer.

The basic stages in the life of a metal building component are quarrying, manufacturing, construction, maintenance and demolition. For metals to be processed large quantities of fossil fuels are being consumed and the metal resources are, of

[4] the production of cement involves chemical and physical reactions. This process is quite energy demanding and can be found in wet or dry kiln.

course, reduced. Apart from these obvious consumptions, transportation is an added factor that increases the material's embodied energy.

The basic advantage in metals is that they are readily recycled and re-used. That is why they have a high value, which is a relief, since it ensures the continuation of metal recycling. Recycling metals can have a positive environmental impact, since it can reduce solid wastes from the land and also reduce the consumption of fossil fuels for the winning, manufacturing and transporting of new metal construction components. Characteristically, recycled metals embody far less energy – as little as 8 GJ/tonne[5]. And it is also a fact that metal industries have considerably reduced energy consumption over the past 20 years. Ideally, if metals were recycled using renewable energy resources, then they would end up having a low embodied energy.

*Plastics*

Plastics are another material group that can be found in the construction industry. Many insulation products are made of plastics, as well as other building components. The most significant plastics are:

Thermoplastics

- polyvinyl chloride (PVC)
- polyethylene
- polystyrene
- polyurethane

Elastomers

- artificial
- natural

Almost all of the plastics mentioned above (apart from natural elastomers) are either made of crude oil or natural gas. As it is known, these two raw materials are, most importantly, used for energy generation. So, by using them in the production of plastics, fossil fuels are directly and indirectly consumed. Known reserves of oil are approximately equal to another 40 years and reserves of natural gas are about 60

[5] Environmental Impact of Materials, Volume A. Construction Industry Research and Information Association (CIRIA), London, 1995

years[6]. Apart from the consumption of fossil fuels, there are tragic environmental impacts in case such as oil spillages from tankers in the sea. However, this refers only to accidents and the effects are localised, and they are not as significant as the need for marine transportation of crude oil.

Oil and gas are converted into feedstock chemicals at refineries. One of the disadvantages of these factories is that they are major installations, which require large areas of land and have a rather negative visual impact on the area were they are situated. For example the refineries that are based at the outskirts of Athens have degraded the area, forcing the residents of nearby areas to migrate.

Apart from the visual and space impacts, oil and natural gas are responsible for emissions of greenhouse gases to the atmosphere, such as organic compounds (VOC's), oxides of sulphur, oxides of carbon and particulates. Another issue is related to the production of chlorine for PVC's. This process is particularly energy demanding, so most emissions are associated with power generation. A further concern of chlorine is its highly toxic ability to plants and animals. However, the chlorine manufacturing industry believes that the use of chlorine in PVC is decreasing[7].

According to CIRIA Report, the energy required foir the extraction of gas and oil from the North Sea are between 3 and 4 MJ/kgr. Typical embodied energies are 45 to 55 MJ/kgr. Thus, the energy needed to win oil and gas is between 6 and 7% of the total energy content of the raw materials. Another table with basic embodied energy values can be seen below:

| material | Energy per mass (MJ/kgr) |
|---|---|
| polyvinyl chloride (PVC) | 58.6 |
| polyethylene | 70 - 86 |

Table 5. A list of the most common plastics used in the construction industry, as published by CIRIA.

[6] "Biceps Module, Facilities Energy Management". British Research Establishment (BRE), 1997
[7] Environmental Impact of Materials, Volume A. Construction Industry Research and Information Association (CIRIA), London, 1995

*Timber*

Timber comprises possibly the only material in the construction industry that comes from a truly renewable resource. However, the continuous use of timber has a concerning environmental impact worldwide. Greece is a country that produces about 35 to 40% of its timber needs. This leaves another 55 to 60% for it to be imported[8]. And importing timber subsequently means that large amounts of fossil fuels are consumed in the transportation of the material.

The timber materials covered by the CIRIA Report were:

- hardwood and softwood
- plywood
- fibreboards, including medium density ones (MDF)
- chipboard
- cork
- rubber
- paper and cardboard and others

The current rate of timber extraction is very high and is continuously leading to the loss of old-growth forestry throughout the world. In tropical areas the problem appears to be larger. Large parts of the forest are being destroyed daily for the production of timber and the creation of agricultural lands. Since trees are contributing in the reduction of CO2, by this destruction it can be realized that CO2 emissions to the atmosphere are increasing. There are also other kinds of problems, such as the destruction of natural habitats, which does not only lead to the extinction of rare animal species but in problems such as flooding in residential areas, close t these forests. Other problems are:

- erosion of soil and loss of fertility
- disruption of the lives of native people
- loss of future resources, especially of new medicine
- loss of biodiversity

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[8], "www. minagri.gr." Website of Greek Ministry of Agriculture [July 2005]

It is sad that of the range of tree species growing in the natural tropical forest, only a small proportion are considered to be of commercial value. And in order to gain access to the valuable ones, the 'non-commercial' trees are sacrificed. However, efforts have been made for the production of sustainable tropical forests and wood collected for these areas is increasingly being sold to the market. The inevitable problem for the designer or the specifiers of buildings is how to be able to select timber that has been sustainably grown and will be replaced by new trees. There are a number of international agreements, certification schemes and codes of practice, but unfortunately, in Greece it is practically impossible to know whether the timber used in a building came from a sustainable source or not.

The energy required to produce certain types of timber can be seen in the table below:

| Material (type of timber) | Density (kgr/m3) | Energy per volume (GJ/m3) |
|---|---|---|
| Rough-sawn timber | 500 | 0.8 |
| Treated timber (air dried) | 500 | 1.2 |
| Glue-laminated timber | 500 | 4.5 |
| Plywood | 500 | 9.4 |
| Particle board | 500 | 12.9 |
| Hardboard | 650 | 20.6 |
| Softboard | 450 | 15.5 |
| paper | 700 | 21.8 |

Table 6. A list of the most common minerals used in the construction industry, as published by CIRIA.

### 3.5 IVAM Research and Consultancy on Sustainability

One of the most important research teams in the field of Life Cycle Assessment is the IVAM Research and Consultancy on Sustainability, based in Amsterdam. It is an innovative research agency active in the areas of chemical risks, sustainable building, energy, chain management, quality of living and cleaner production. The agency is affiliated to the University of Amsterdam.

IVAM has produced a computer program, which specializes in the embodied energy of materials in general, not only the ones involved with the construction industry. This software is called SimaPro 6, and stands for "System for Integrated Environmental Assessment of Products". It provides a professional tool to collect, analyze and monitor the environmental performance of products and services.

For the last ten years, IVAM has been carrying out Life Cycle Assessments (LCAs) on behalf of the business community and the government. During a life cycle assessment, the environmental impact of a product, process or service is determined according to standardized methods that satisfy the requirements of ISO 14042[9]. For several clients, including the Ministry of Housing, Spatial planning and the Environment, the Directorate-General for Public Works and Water Management and the EU, IVAM has worked on a number of methodological aspects of LCA including standardization, weighting, allocation and data quality.

The British Research Establishment has been cooperating with the IVAM team. Moreover, some of the data, concerning the embodied energy of certain construction materials of this Report were taken from the LCA database of IVAM.

The following chapter includes the analysis and calculations of the embodied energy of construction materials of the house chosen.

[9] IVAM website < www.ivambv.uva.nl/> [July 2005]

# Chapter 4. Method

### 4.1 Scope of the analysis

This Report comprises an attempt to estimate the total embodied energy of a suburban detached house at the outskirts of Athens, Greece. This house, though it includes all the typical construction materials of the area, does not comprise a typical architectural example. The design of the house has a 'bioclimatic' approach, with high levels of insulation (5 times more than the typical), carefully designed apertures, shading devices and double glazing with low emissivity coating.

An important decision to be made from the beginning was on which elements of the building should be included in the embodied energy calculations. In this report, it was decided to include all the basic constructional elements, the wall and floor finishes. Unfortunately, building services and fittings were not included, since they placed constraints and were also considered to be a very objective decision for the specifier.

### 4.2 Structure of the Study

The building that was used for this study was on site during the Report writing, so all the information had to be taken from the drawings, using simple measurements. For ease of the calculations the building was separated into several major categories:

- Floors
- External walls
- Internal walls
- Glazed areas

For some components there was not enough information available from the plans to accurately calculate the quantities used. At such cases, assumptions were made as to the components and the quantities of materials used in the building. For instance, the house has a semi-basement floor, but the external finishes were assumed to apply on the full height of the semi-basement external wall.

### 4.3 General site and building information

The house that is surrounded by blocks of flats and 2 storey houses, is situated at a site on the dead-end of a road (see appendix 1). The building is facing south/south east and is not allowed to have any openings on the northern part of the site. It includes a semi-basement floor, a raised ground floor and a small attic. The total area of the site is 240 m2 and the area of the building is about 175 m2, on all the floors.

The house itself has an open plan living room and kitchen, as well as a study room and a WC on the ground floor. All the bedrooms, a bathroom and a storage space are located on the basement. The attic has a small room that opens out to the roof garden.

### 4.4 Construction materials

The typical materials used for the construction of a suburban house in Greece are:

- The foundation, floors, beams and columns are made of reinforced concrete. The concrete type is C2025, which is suggested by the Greek Law. The type of steel used in this case is S500S.
- External walls are made of two series of clay bricks and extruded polystyrene insulation (Dow) in the cavity between.
- The walls are plastered externally and internally
- All the windows will be timber frame and will have double glazing units.
- The floors internally will be cladded with timber (clay tiles in the bathrooms).
- The insulation used on the roof as well as the walls will be extruded polystyrene (Dow)
- The walls surrounding the site will be made of reinforced concrete and will be cladded with stone found on the site
- There will be timber shutters for solar protection and security
- In some case, vertical shading devices will be applied, in order to minimize the solar penetration during hot summer days.
- There rest of the site (150 m2) will be left open to include a garden and a parking space.

All the materials used are typical in the area and will be provided from local distributors and manufacturers. These are the materials to be used in reality for this building. However, for the sake of this study, different scenarios will be tried out. There is an extensive reference to them in the next sub-chapter.

Unfortunately, no research has been done for the embodied energy of construction materials in Greece. That is why the basic source for the data of this Report was the British Research Establishment (BRE), the IVAM group in Holland, the Construction Information Research and Association (CIRIA), and the DBRI research team from Denmark. All these groups have published detailed tables of the embodied energy of all the major construction materials. However, at some points, data from Australia, Canada and New Zealand research groups were used (see appendix 2).

### 4.5 Assumptions and calculation methodology

There will be different case scenarios throughout this study. These scenarios are not taken in random. These are real options that the Greek specifiers always take into account. Here is an indication:

- change of insulation material (glass wool or extruded polystyrene)
- change of external wall construction (bricks or concrete blocks)
- change of window frame material (timber or aluminum)
- change of floor material (timber or local marble)
- doubling of insulation (from 150 mm to 300 mm thickness)

It should be mentioned that no other construction option will be tried out, since it would not have a practical application in a country like Greece, due to the extensive problem with earthquakes. Moreover, clay tiles are assumed to be placed in the bathrooms in all the scenarios, as the most common option. Finally all the different scenarios are summarized in the table 1.

| | *STRUCTURE* | *WALLS* | *FLOORS* | *OTHER FEATURES* |
|---|---|---|---|---|
| **TYPICAL CASE** | reinforced concrete | - clay bricks<br>- extruded polystyrene<br>- plaster | timber | timber frame windows |
| **CASE SCENARIO 1**<br>Wall material change | reinforced concrete | **- concrete blocks**<br>- extruded polystyrene<br>- plaster | timber | timber frame windows |
| **CASE SCENARIO 2**<br>Insulation material change | reinforced concrete | - clay bricks<br>**- glass wool**<br>- plaster | timber | timber frame windows |
| **CASE SCENARIO 3**<br>Floor material change | reinforced concrete | - clay bricks<br>- extruded polystyrene<br>- plaster | **marble (local)** | timber frame windows |
| **CASE SCENARIO 4**<br>Window frame material change | reinforced concrete | - clay bricks<br>- extruded polystyrene<br>- plaster | timber | **aluminum frame windows** |
| **CASE SCENARIO 5**<br>Doubling of insulation **(300 mm thickness)** | reinforced concrete | - clay bricks<br>- extruded polystyrene<br>- plaster | timber | timber frame windows |

Table 1. Showing all the different case scenarios that will be tested.

Total volume of reinforced concrete (30 MPa) = **111 m3 ok**

Total mass of steel used in reinforced concrete = **2,313 kgr ok**

Total external wall surface (excluding concrete columns) = **139 m2 ok (concrete area 93 m2)**

Total external wall surface (including concrete columns) = **232 m2 ok**

Total glazed area = **59.525 m2 ok**

Total floor area (timber or marble) = **171.57 m2 ok**

Total floor and wall area (clay tiles) = **15.85 m2 ok**

Total plastered surfaces = external wall area (internally and externally)+ internal wall area + ceiling area = **232 m2** + **232 m2** + **34.24 m2** + **155 m2 ok**

= **653.24 m2 ok**

Assumption: the insulation used was 150 mm thick and the insulation applied on the external part of the concrete columns was 30 mm thick. This means that if one unit of insulation is applied on the concrete columns, then 5 units should be calculated for the cavity of the brick walls.

### 4.6 Typical Case Scenario

In the typical case scenario it is assumed that the materials used for the construction of the building are:

- reinforced concrete on the building frame and foundation
- bricks on the external walls
- plaster on the external walls, internal walls and ceilings
- timber on all the floors, apart from the bathroom
- clay tiles on the bathroom walls and floor
- timber window frames
- double glazing on all the apertures
- extruded polystyrene insulation

In this case the table that followed all the calculations can be seen below. (Table 2). The amount of 860,903 MJ is the energy spent in the construction materials of the case study that is being tested. All the materials represent the most commonly used materials in urban Greece. This is a fact that can contribute in the final conclusions of the analysis and can comprise a generic view on the embodied energy of Greek houses.

| material | Embodied energy MJ/kgr MJ/m3 | | Mass or Volume of case study material (kgr or m3) | Embodied energy of case study material (MJ) |
|---|---|---|---|---|
| Concrete (structural) | 1.9 | 4,465 | **111 m3** | **495,615** |
| Steel (for concrete reinforcement) | 38 | | **2,313 kgr** | **87,894** |
| Clay bricks* | 2.5 | 5,170 | **22,384 kgr** | **55,960** |
| Plaster | 4.5 | 6,460 | **13.06 m3** | **84,367** |
| Extruded polystyrene insulation (Dow) | 117 | 3.770 | **25.50 m3** | **96,135** |
| Kiln dried timber | 5 | - | **3,600 kgr** | **18,000** |
| Clay tiles | 6.8 | - | **1,981 kgr** | **13,472** |
| Glass | 15.9 | 40,060 | **595 kgr** | **9,460** |
| Local stone | 0.8 | 1,890 | - | - |
| *Functional Unit: MJ/kgr or MJ/m3* | | | **Total** | **860,903** |

Table 2. showing the embodied energy of all the construction materials of the house, in the typical case scenario

*According to the Greek Brick Industry, 1m2 area of bricks weighs 10 kgr[1].

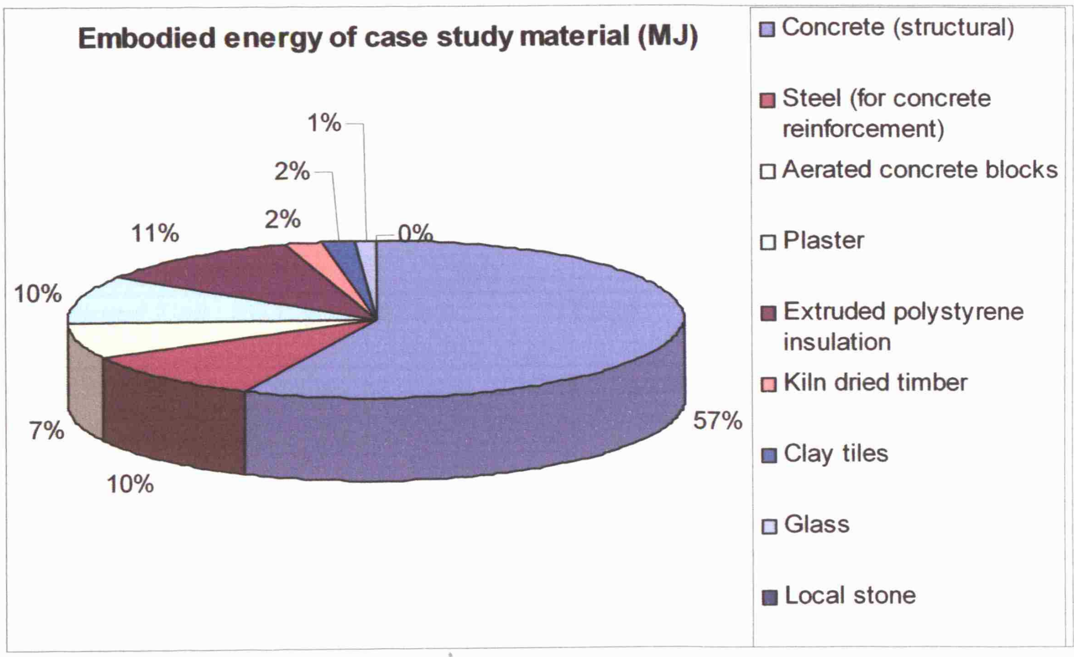



Figure 1. Showing the different values of embodied energy of construction materials in the typical case scenario.

[1] http://www.bricks.gr/mainEn.htm [August 2005]

### 4.7 Case Scenario 1 (Change of external wall construction)

In Case Scenario 1, it was decided to replace the clay bricks with aerated concrete blocks. As mentioned earlier, this is a realistic approach, since both of these products are currently being used in the Greek construction market. In this case it can be observed that the total amount of embodied energy is 868,188 MJ. Even though the total weight of the aerated blocks is smaller than the weight of the bricks, the total amount of embodied energy is increased. This is due to the larger embodied energy of the concrete aerated blocks (3.5 MJ/kgr as opposed to 2.5 of the clay bricks).

| material | Embodied energy MJ/kgr MJ/m3 | | Mass or Volume of case study material (kgr or m3) | Embodied energy of case study material (MJ) |
|---|---|---|---|---|
| Concrete (structural) | 1.9 | 4,465 | **111 m3** | **495,615** |
| Steel (for concrete reinforcement) | 38 | | **2,313 kgr** | **87,894** |
| Aerated concrete blocks | 3.5 | - | **18,070 kgr** | **63,245** |
| Plaster | 4.5 | 6,460 | **13.06 m3** | **84,367** |
| Extruded polystyrene insulation (dow) | 117 | 3.770 | **25.50 m3** | **96,135** |
| Kiln dried timber | 5 | - | **3,600 kgr** | **18,000** |
| Clay tiles | 6.8 | - | **1,981 kgr** | **13,472** |
| Glass | 15.9 | 40,060 | **595 kgr** | **9,460** |
| Local stone | 0.8 | 1,890 | - | - |
| *Functional Unit: MJ/kgr or MJ/m3* | | | **Total** | **868,188** |

Table 3. Showing the embodied energy of all the construction materials of the house, in the first case scenario

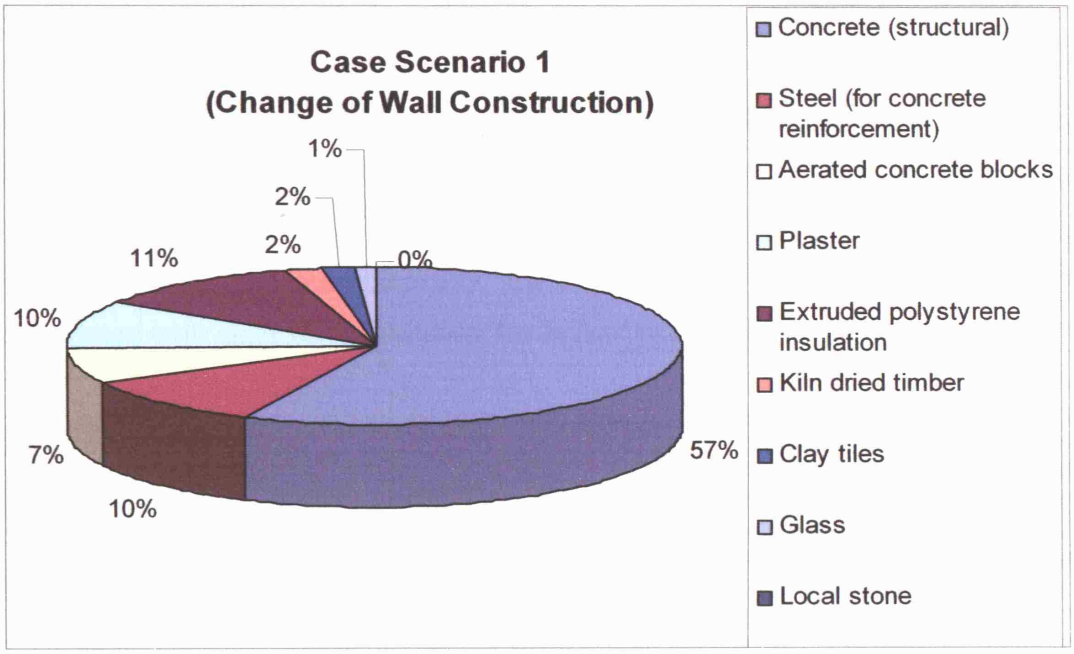



Figure 2. Showing the different values of embodied energy of construction materials in the first case scenario (were aerated concrete blocks are used instead of clay bricks).

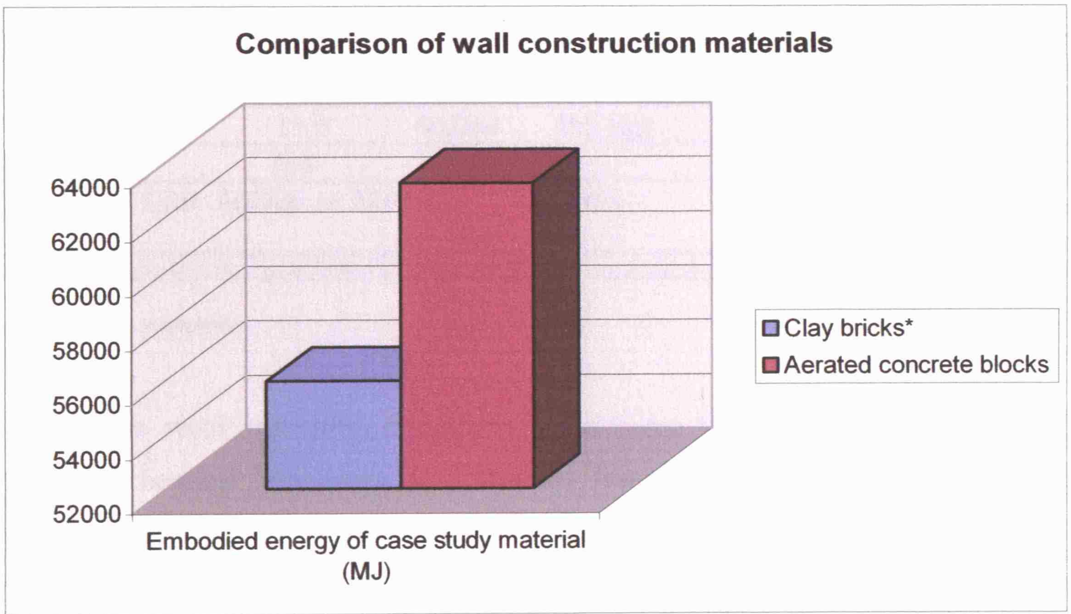



Figure 3. Showing the different values of embodied energy of aerated concrete blocks and clay bricks.

### 4.8 Case Scenario 2 (Insulation change)

The two typical types of insulation that are currently being used in the Greek Construction Industry are extruded polystyrene (often known as Dow) and glass wool insulation. Though extruded polystyrene is most commonly used, glass wool has the ability to insulate not only thermally, but also acoustically. By replacing extruded polystyrene with glass wool insulation, the following table was formed:

| material | Embodied energy MJ/kgr MJ/m3 | | Mass or Volume of case study material (kgr or m3) | Embodied energy of case study material (MJ) |
|---|---|---|---|---|
| Concrete (structural) | 1.9 | 4,465 | **111 m3** | **495,615** |
| Steel (for concrete reinforcement) | 38 | | **2,313 kgr** | **87,894** |
| Clay bricks* | 2.5 | 5,170 | **22,384 kgr** | **55,960** |
| Plaster | 4.5 | 6,460 | **13.06 m3** | **84,367** |
| Glass wool insulation | 31 | 620 | **25.50 m3** | **15,810** |
| Kiln dried timber | 5 | - | **3,600 kgr** | **18,000** |
| Clay tiles | 6.8 | - | **1,981 kgr** | **13,472** |
| Glass | 15.9 | 40,060 | **595 kgr** | **9,460** |
| Local stone | 0.8 | 1,890 | - | - |
| *Functional Unit: MJ/kgr or MJ/m3* | | | **Total** | **780,578** |

Table 4. Showing the embodied energy of all the construction materials of the house, in the second case scenario

Since glass wool insulation comprises a substance that follows a 'lighter', less complex chemical procedure, it consumes less energy during its manufacture. Extruded polystyrene 'spends' 118 MJ per kgr of the material, whereas glass wool consumes only 31 MJ per kgr. Thus, the total embodied energy of the construction materials of the house was reduced by around 80,000 MJ.

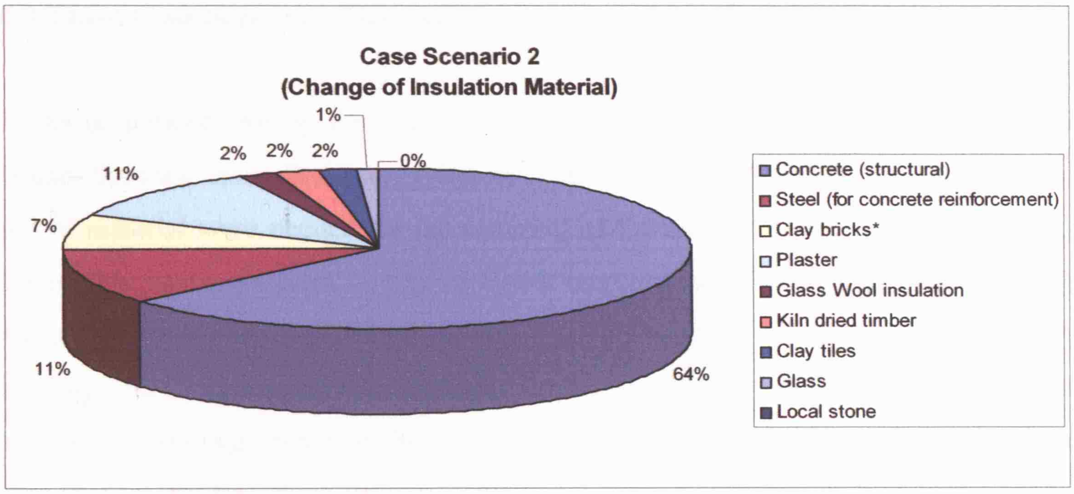



Figure 4. Showing the different values of embodied energy of construction materials in the second case scenario (where extruded polystyrene insulation is being replaced by glass wool insulation).

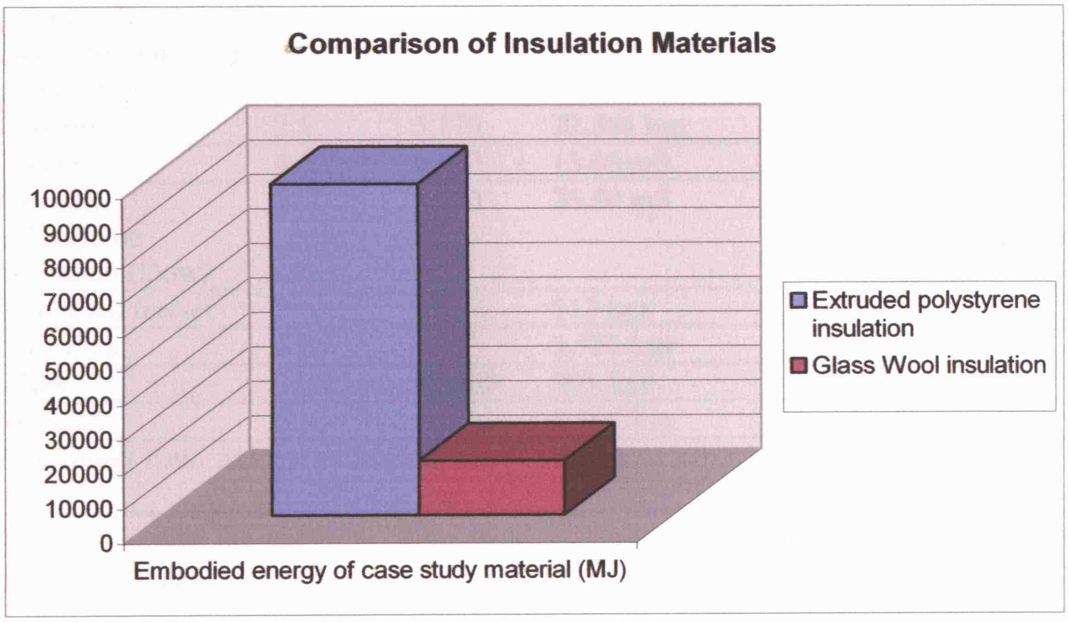



Figure 5. Showing the different values of embodied energy of extruded polystyrene insulation and glass wool insulation.

### 4.9 Third Case Scenario (Floor material change)

It can be noticed that by the replacement of timber with marble -on the floor of the house- the total embodied energy was increased significantly. Even though only 3.43 m3 of material were needed for the covering of the interior floors, still the weight of the marble was quite high. A typical Greek marble (e.g. Dionysus off-white marble) has a density of about 2,700 kgr per m3. This fact raises its embodied energy per kgr instantly. So in the typical case scenario, timber was used for the floors and its weight was about 3,000 kgr, whereas the amount of marble needed to replace the timber floor was about 9,000 kgr (three times heavier).

| material | Embodied energy MJ/kgr | MJ/m3 | Mass or Volume of case study material (kgr or m3) | Embodied energy of case study material (MJ) |
|---|---|---|---|---|
| Concrete (structural) | 1.9 | 4,465 | **111 m3** | **495,615** |
| Steel (for concrete reinforcement) | 38 | | **2,313 kgr** | **87,894** |
| Clay bricks | 2.5 | 5,170 | **22,384 kgr** | **55,960** |
| Plaster | 4.5 | 6,460 | **13.06 m3** | **84,367** |
| Extruded polystyrene insulation (Dow) | 117 | 3.770 | **25.50 m3** | **96,135** |
| Kiln dried timber | 5 | - | **513 kgr** | **2,565** |
| Clay tiles | 6.8 | - | **1,981 kgr** | **13,472** |
| Glass | 15.9 | 40,060 | **595 kgr** | **9,460** |
| Marble* | 5.9 | - | **9,261 kgr** | **54,640** |
| *Functional Unit: MJ/kgr or MJ/m3* | | | **Total** | **900,108** |

Table 5. Showing the embodied energy of all the construction materials of the house, in the third case scenario

** since no specific values were found to characterize the embodied energy of Greek marble, the value of granite, calculated by the Australian CSIRO was taken.*

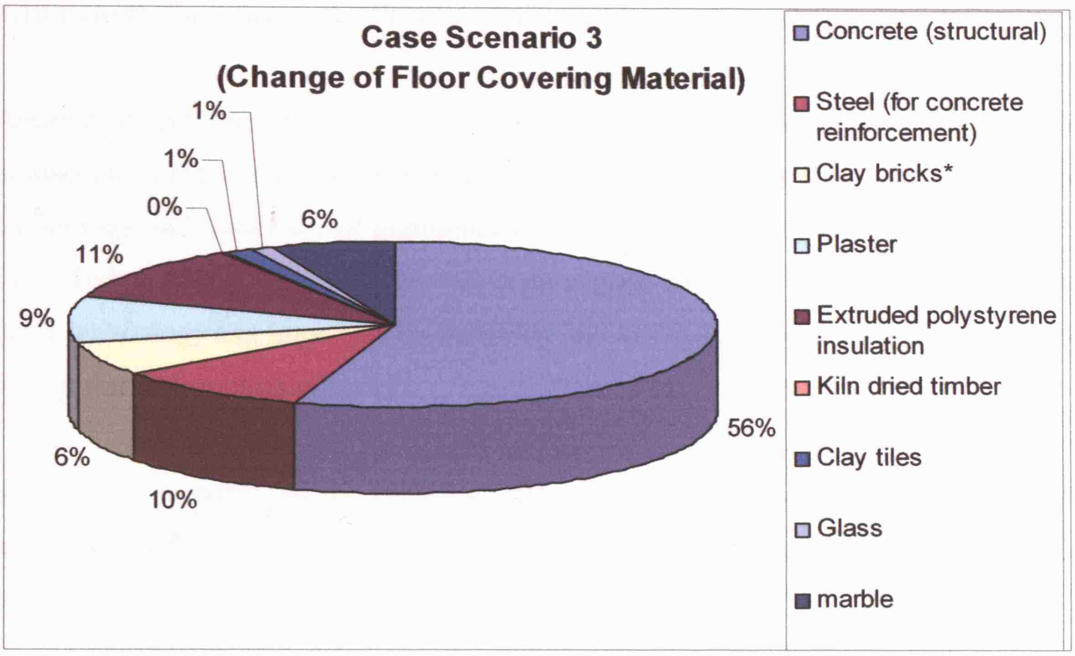



Figure 6. Showing the different values of embodied energy of construction materials in the third case scenario (where timber floor is being replaced by marble floor).

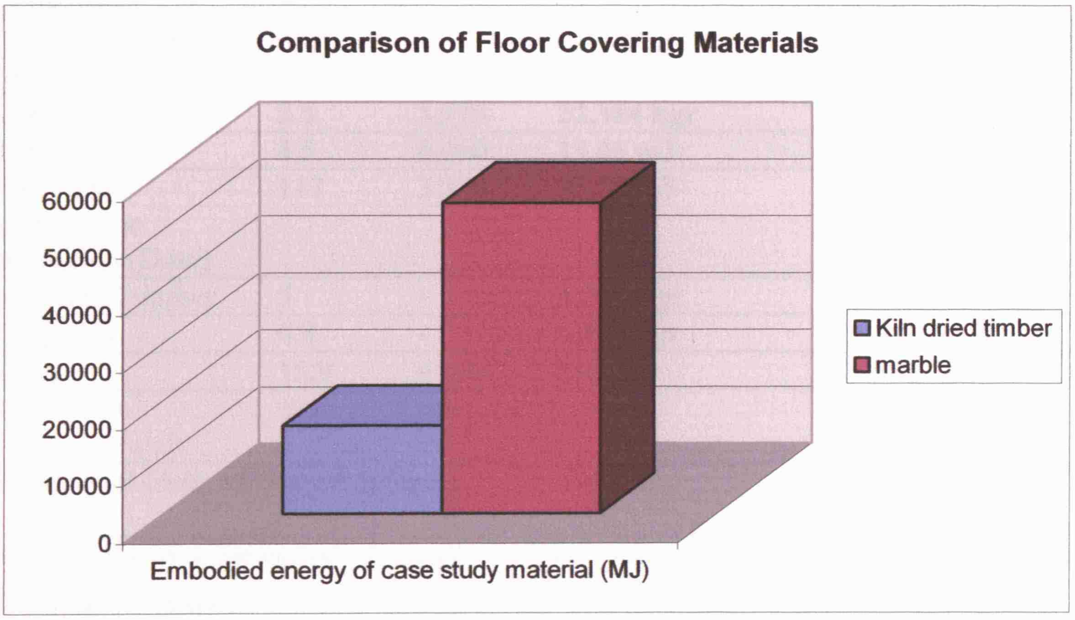



Figure 7. Showing the different values of embodied energy of the floor covering materials in both cases (typical and third case scenario)

### 4.10 Fourth Case Scenario (Window frame material change)

Another typical dilemma of Greek architects and clients has been the use of timber or aluminum on the window frames of the houses. Timber was traditionally used, but the technology and durability of aluminum has put the material on the top of the choice lists. Today, though, the industry has seen a great turn to timber framed windows, since technology has improved its durability and aesthetics have always played a great role in the construction industry.

In this case scenario, all the timber window frames that are in reality chosen by the architects, will be replaced theoretically by aluminum ones. In such a case, the table below shows the new data:

| material | Embodied energy MJ/kgr MJ/m3 | | Mass or Volume of case study material (kgr or m3) | Embodied energy of case study material (MJ) |
|---|---|---|---|---|
| Concrete (structural) | 1.9 | 4,465 | **111 m3** | **495,615** |
| Steel (for concrete reinforcement) | 38 | | **2,313 kgr** | **87,894** |
| Clay bricks* | 2.5 | 5,170 | **22,384 kgr** | **55,960** |
| Plaster | 4.5 | 6,460 | **13.06 m3** | **84,367** |
| Extruded polystyrene insulation (Dow) | 117 | 3.770 | **25.50 m3** | **96,135** |
| Kiln dried timber | 5 | - | **3,087 kgr** | **15,435** |
| Clay tiles | 6.8 | - | **1,981 kgr** | **13,472** |
| Glass | 15.9 | 40,060 | **595 kgr** | **9,460** |
| Aluminum (New Zealand) | 191 | - | **513 kgr** | **97,983** |
| *Functional Unit: MJ/kgr or MJ/m3* | | | **Total** | **956,321** |

Table 6. Showing the embodied energy of all the construction materials of the house, in the fourth case scenario.

This case scenario has given the highest results so far. From 860,903 MJ found in the typical case scenario of the house, by replacing the timber windows to aluminium ones, the total embodied energy of the construction materials was increased to 956,321 MJ. There is a 10% increase, which is quite significant. In the next step of this process, where operational energy (energy in use) will be calculated, it will be interesting to see the difference such window frames would make in the annual heating and cooling load.

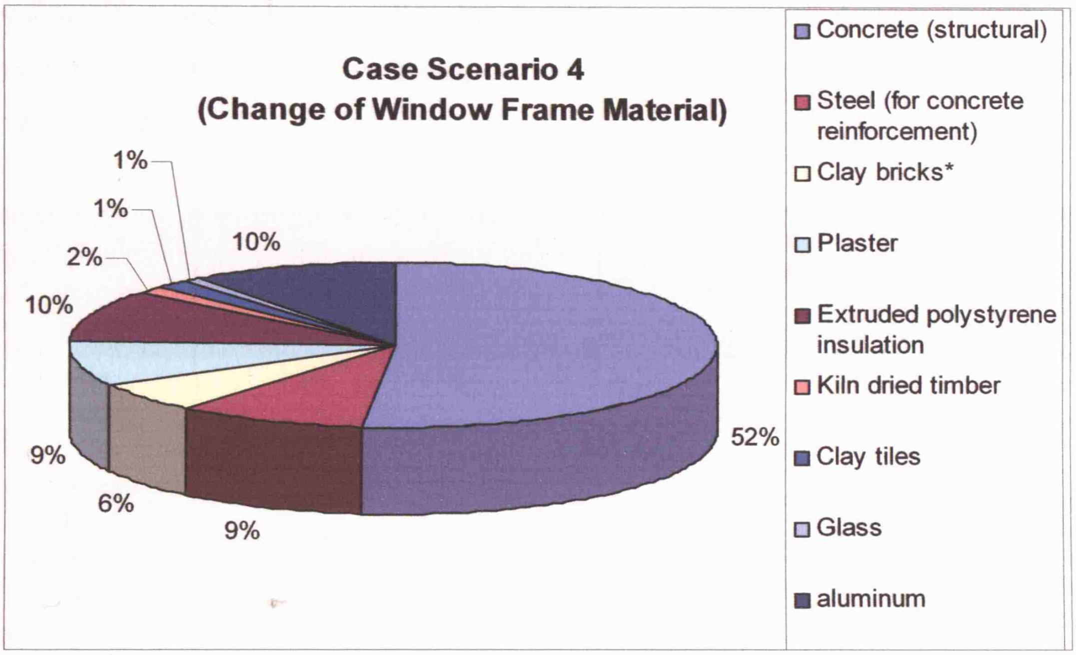



Figure 8. Showing the different values of embodied energy of construction materials in the fourth case scenario (where timber windows are being replaced by aluminum ones).

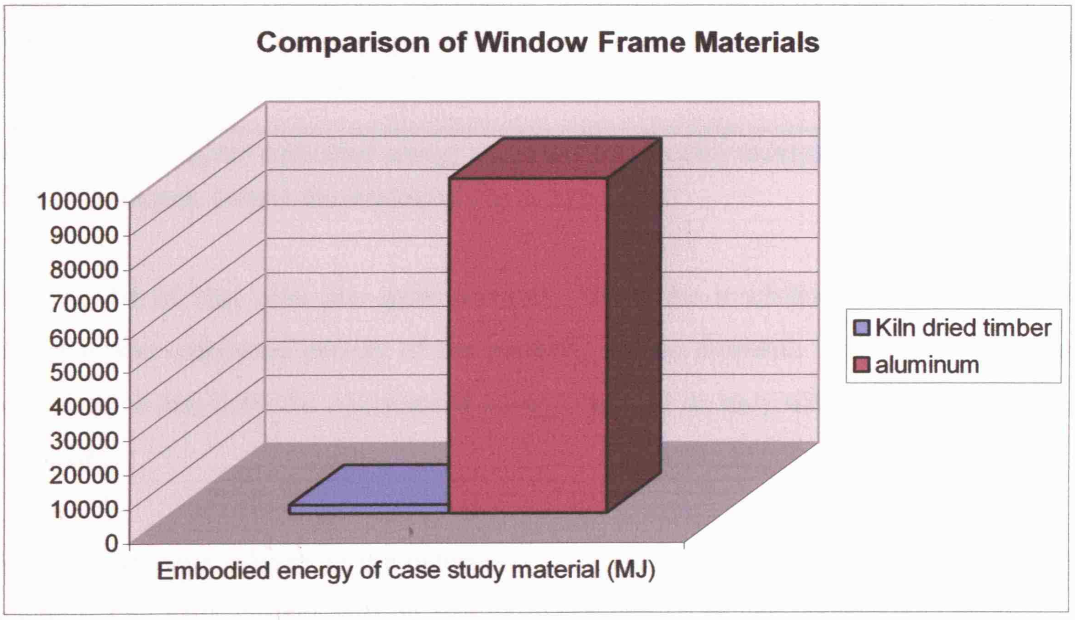



Figure 9. Showing the different values of embodied energy of the window frame materials in both cases (typical and fourth case scenario).

### 4.13 Fifth Case Scenario

In this final case scenario the same materials as the case study were applied. The difference was that the amount of insulation used was doubled. Naturally, the total amount of embodied energy will be increased, but the interesting element would be to see how much and in what percentage relative to the case study. The following table was concluded:

| material | Embodied energy MJ/kgr MJ/m3 | | Mass or Volume of case study material (kgr or m3) | Embodied energy of case study material (MJ) |
|---|---|---|---|---|
| Concrete (structural) | 1.9 | 4,465 | **111 m3** | **495,615** |
| Steel (for concrete reinforcement) | 38 | | **2,313 kgr** | **87,894** |
| Clay bricks* | 2.5 | 5,170 | **22,384 kgr** | **55,960** |
| Plaster | 4.5 | 6,460 | **13.06 m3** | **84,367** |
| Extruded polystyrene insulation (Dow) | 117 | 3.770 | **51 m3** | **192,270** |
| Kiln dried timber | 5 | - | **3,600 kgr** | **18,000** |
| Clay tiles | 6.8 | - | **1,981 kgr** | **13,472** |
| Glass | 15.9 | 40,060 | **595 kgr** | **9,460** |
| Local stone | 0.8 | 1,890 | - | - |
| *Functional Unit: MJ/kgr or MJ/m3* | | | **Total** | **957,038** |

Table 7. Showing the embodied energy of all the construction materials of the house, in the fifth case scenario (where the insulation was doubled).

The results of this case are quite obvious. When the insulation of the building is doubled, the embodied energy of the material is also doubled. The interesting point would be to see how the operational energy (energy in use) will be affected by this increase.

This chapter was related to the calculations for the embodied energy of the building studied. The next chapter will be related to the energy in use (operational energy) of the building as well as the thermal simulation, which will give the corresponding results.

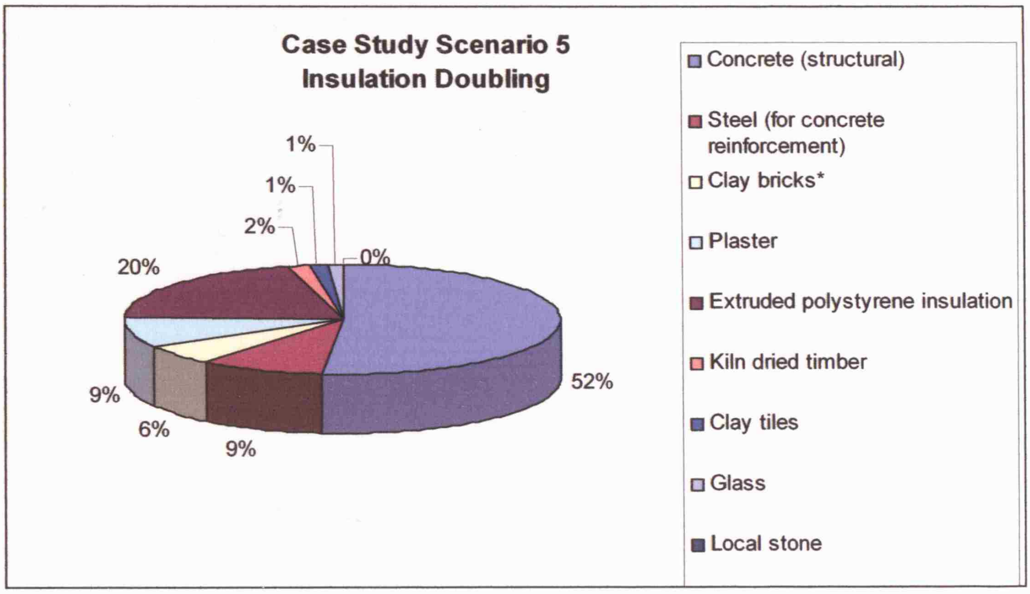


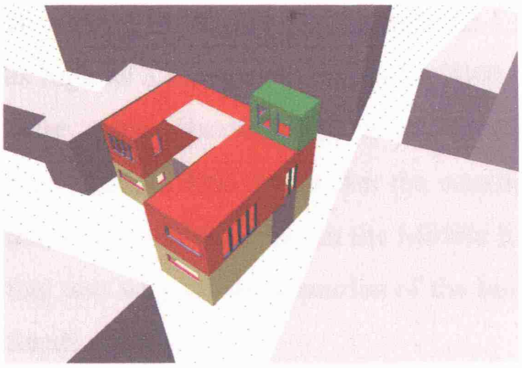

Figure 10. Showing the different values of embodied energy of construction materials in the fourth case scenario (where insulation thickness was doubled).

# Chapter 5. Thermal Simulation of Operational Energy

### 5.1 TAS Modelling and Simulation

In the previous chapter the embodied energy of the construction materials of the house were calculated. This chapter includes the procedure and the calculations for the operational energy (energy in use) of the case study. The computer program that was used is called TAS (Thermal Analysis Simulation) and it simulates the dynamic thermal performance of buildings and their systems.

At the beginning, the model of the house and its surrounding buildings was drawn in the 3D Modeller of TAS (Figure 1 & 2). Then the model was exported to the Building Simulation of the software. In this part, all the data regarding the construction materials and sizes, the internal conditions of the building and the weather of the area were introduced (see appendix 2). After all this information input, the file was ready for simulation.



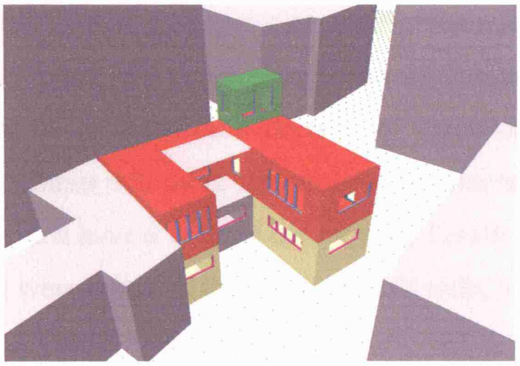


Figure 1 & 2. Images of the 3D model of the house, drawn in TAS 3D Modeller.

The construction materials chosen have already been analytically mentioned in the previous chapter. The internal conditions selected for the building were:

- there are 4 occupants, which are away from 9:00 am to 5:00 pm. This means that during these hours of the day no internal gains were included
- there was a lighting schedule, which allowed the lights to be on from 8:00 pm until 1:00 am
- the thermostat had a lower limit to 20 degrees Celsius and an upper limit to 25 degrees Celsius. This means that when the temperature fell below 20 degrees,

then the heating started working, and when the temperature reached 25 degrees Celsius, the air conditioning was on.

Six different simulations were run, in order to have the results for the case study scenario and the other 5 different scenarios. The weather file that was chosen is the Athens weather for the year 1979. At this point there was a significant decision to be made. Since the embodied energy of the construction materials was calculated for a 60 year life span, this had quite an impact on the calculations of the operational energy. The operational energy is calculated for one year and then it functions cumulatively. So, for example if the annual operational energy was 20,000 kWh, then for a period of 60 years it would be 20,000 x 60 = 120,000 kWh. But the climate change predictions refer to an increase of the temperature in Athens. This led to a decision to test the same case scenarios on a different weather file: something that would be more representative of the weather of Athens in 60-years time.

According to chapter one, paragraphs 1.5.1 and 1.5.2, the temperature may increase to as high as 3.5 degrees Celsius by 2050. Furthermore, the predictions for precipitation were quite discouraging, since they refer to a significant decline of summer precipitation. This meant that the weather of Athens will more and more be similar to the weather of the cities in the Middle East, which have a hot and dry climate. Finally, that was why all six scenarios of the building were tested in the weather of Riyadh, in Saudi Arabia.

### 5.2 Thermal Simulation Results

All six scenarios were tested in the TAS program. The interesting part of the results was the annual heating and cooling load. This would reveal the energy that the occupiers would spent for heating and cooling the house. 12 different simulations were tested and the tables below summarize the results:

| WEATHER: ATHENS | Annual operational energy (kWh) | Annual operational energy per floor area (kWh/m2) | Percentage of change (%) |
|---|---|---|---|
| **Typical case scenario** | 29,266 | 177 | - |
| **Case scenario 1** **Wall material change** | 29,107 | 166 | -0.5% |
| **Case scenario 2** **Insulation material change** | 29,240 | 167 | -0.08% |
| **Case scenario 3** **Floor material change** | 29,233 | 167 | -0.1% |
| **Case scenario 4** **Window material change** | 29,365 | 167.8 | +0.3 |
| **Case scenario 5** **Doubling of insulation** | 28,700 | 164 | -1.9% |

Table 1. Showing the results of the annual operational energy in all six case study scenarios.

| WEATHER: ATHENS | Annual operational energy (kWh) | Annual Heating Load (kWh) | Annual Cooling Load (kWh) |
|---|---|---|---|
| **Typical case scenario** | 29,266 | 26,545 | 2,722 |
| **Case scenario 1** **Wall material change** | 29,107 | 26,350 | 2,756 |
| **Case scenario 2** **Insulation material change** | 29,240 | 26,523 | 2,717 |
| **Case scenario 3** **Floor material change** | 29,233 | 26,531 | 2,702 |
| **Case scenario 4** **Window material change** | 29,365 | 26,570 | 2,794 |
| **Case scenario 5** **Doubling of insulation** | 28,700 | 26,091 | 2,608 |

Table 2. Showing the results of the annual heating and cooling load (Athens).

| WEATHER: RIYADH | Annual operational energy (kWh) | Annual operational energy per floor area (kWh/m2) | Percentage of change (%) |
|---|---|---|---|
| **Typical case scenario** | 22,336 | 135 | - |
| **Case scenario 1** **Wall material change** | 22,080 | 126 | -1.0% |
| **Case scenario 2** **Insulation material change** | 22,296 | 127 | -0.17% |
| **Case scenario 3** **Floor material change** | 22,291 | 127 | -0.2% |
| **Case scenario 4** **Window material change** | 22,659 | 129.5 | +1.4% |
| **Case scenario 5** **Doubling of insulation** | 21,438 | 122.5 | -4.0% |

Table 3. Showing the results of the annual operational energy in all case study scenarios.

| WEATHER: RIYADH | Annual operational energy (kWh) | Annual Heating Load (kWh) | Annual Cooling Load (kWh) |
|---|---|---|---|
| **Typical case scenario** | 22,336 | 7,311 | 15,025 |
| **Case scenario 1** **Wall material change** | 22,080 | 7,316 | 14,764 |
| **Case scenario 2** **Insulation material change** | 22,296 | 7,306 | 14,990 |
| **Case scenario 3** **Floor material change** | 22,291 | 7,295 | 14,996 |
| **Case scenario 4** **Window material change** | 22,659 | 7,306 | 15,353 |
| **Case scenario 5** **Doubling of insulation** | 21,438 | 7,186 | 14,252 |

Table 4. Showing the results of the annual heating and cooling load (Riyadh)

As a general conclusion for all the cases tested, is that the house would perform better in a hotter and drier climate, such as Riyadh City. The truth is that before the simulation, it was believed that the simulations with the Athens weather would have a lower total of cooling and heating load, simply because it has a temperate climate. That is not really the case. After the simulation was performed, Riyadh gave better overall results, in terms of energy load. Tables 2 & 4 reveal the fact that when the house was simulated in the weather of Riyadh, the cooling loads were significantly increased. Obviously that was not enough, since the heating loads fell remarkably.

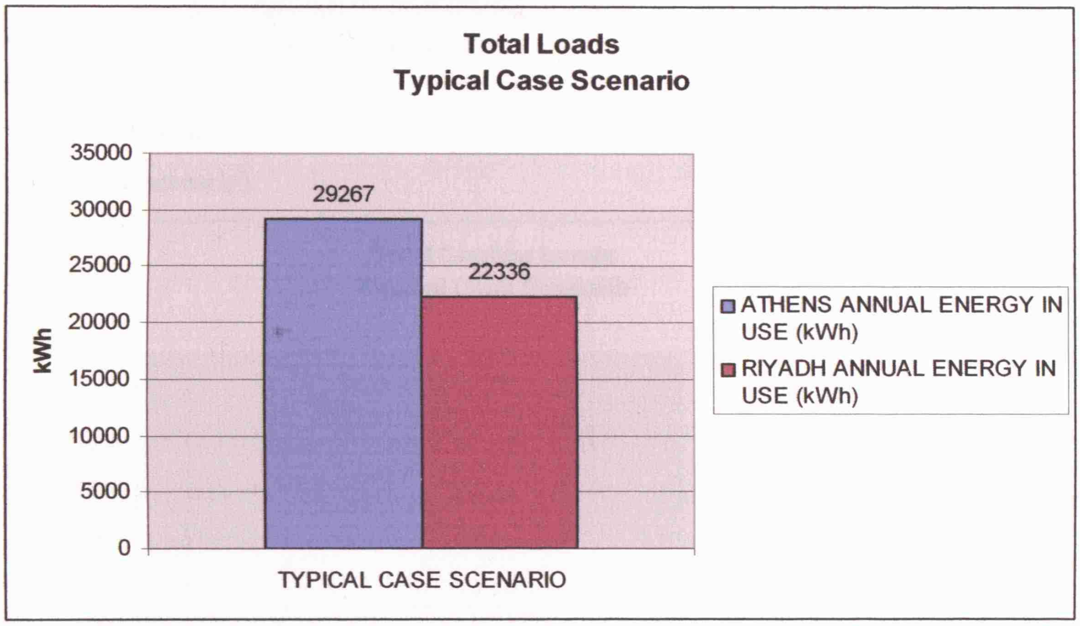



Figure 3. Showing the two different values of the operational energy in both climatic cases (for the typical case scenario).

In figure 3, one can observe that the overall annual energy in use (that is the heating and cooling loads) decreased by 24%. A difference between 23 and 24% was observed in all six case study scenarios. This means that the house would operate better in Riyadh climatic conditions rather than in Athens conditions. This is not a disadvantage, since the weather file for Athens was dated 1979 and the weather has been much hotter since then. The final conclusion is that as the weather will be becoming hotter throughout the years (according to the climate change predictions) the house will be performing better, in terms of operational energy.

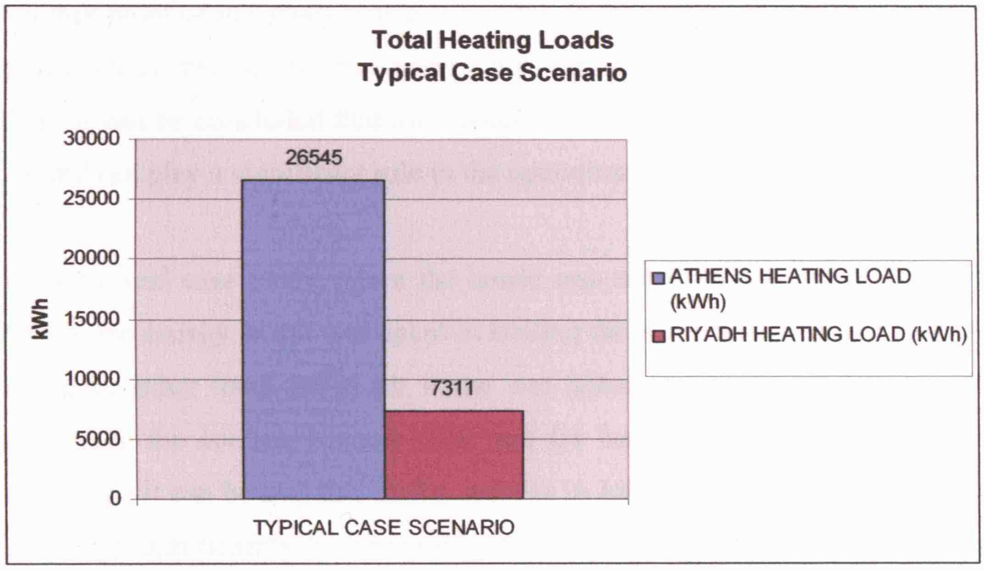



Figure 4. Showing the two different values of the heating loads in both climatic cases (for the typical case scenario).

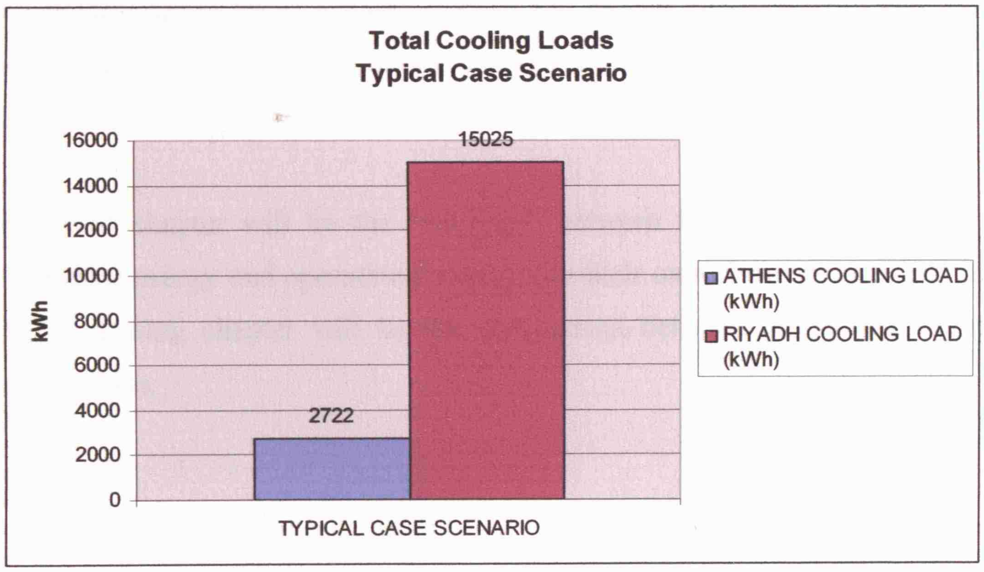



Figure 5. Showing the two different values of the cooling loads in both climatic cases (for the typical case scenario).

| Percentage of difference for total loads (Athens/Riyadh) | Percentage of difference for heating loads (Athens/Riyadh) | Percentage of difference for cooling loads (Athens/Riyadh) |
|---|---|---|
| -24% | -72% | +82% |
| -24% | -72% | +81% |
| -24% | -72% | +82% |
| -24% | -73% | +82% |
| -23% | -73% | +82% |
| -25% | -73% | +82% |

Table 5. Percentage differences in loads, between the two cities(for all six scenarios)

Another point of this study is that in all five different case scenarios (compared to the typical case), the operational energy did not go through any meaningful changes. Thus, it can be concluded that the changes of the specific materials, which were tried out, did not play a significant role in the operational energy.

In the typical case study, when the house was tested in Athens weather conditions, 90% of the energy in use was spent in heating the house and the other 10% in cooling it. On the other hand, when the house was tested in Riyadh weather conditions, the percentage for cooling became 67% and for heating dropped down to 33%. As a conclusion it can be said that as the weather in Athens will become hotter, the cooling loads will significantly be increased. The other point that can be made is that in the current weather conditions in Athens, the largest part of the annual energy in use is consumed for the heating of the house. This means that architects in Greece should focus their design more towards shading and cooling the house properly, rather than investing in great heating solutions. These will not be of a great use in a few decades from now.

The next chapter will be the 'marriage' between the previous two. The data of embodied energy and operational energy (on their own) have already been analyzed. The following chapter will be the comparison between the two different energy calculations.

# Chapter 6. Analysis

### 6.1 Comparison of embodied energy and energy in use (operational energy)

Chapter 4 included an analysis of the embodied energy of all six case scenarios. As it has been mentioned earlier, all the different cases comprise a pragmatic approach to the choices that designers and specifiers have today, relative to the construction materials in Greece. In order to summarize what was concluded for the embodied energy of all six case scenarios, the following table can be used:

| | EMBODIED ENERGY (kWh) | OPERATIONAL ENERGY (kWh) ATHENS | OPERATIONAL ENERGY (kWh) RIYADH |
|---|---|---|---|
| TYPICAL CASE SCENARIO | 239,140 | 29,267 | 22,336 |
| CASE SCENARIO 1 Wall material change | 241,163 | 29,106 | 22,080 |
| CASE SCENARIO 2 Insulation material change | 216,827 | 29,240 | 22,296 |
| CASE SCENARIO 3 Floor material change | 250,030 | 29,233 | 22,291 |
| CASE SCENARIO 4 Window frame material change | 265,645 | 29,365 | 22,659 |
| CASE SCENARIO 5 Insulation doubling | 265,843 | 28,699 | 21,438 |

Table 1. Showing the total embodied energy and operational energy calculated for all the different case scenarios.

From the graph in figure 1, it can be noticed that generally, the embodied energy of the building will be overtaken by the operational energy (assuming the lifespan of the building to be 60 years). More specifically, in the case of the Athens weather simulation, it would take about 8 years for the energy in use to overtake the embodied energy. On the other hand, in the case of a hotter and drier climate (Riyadh) the energy in use would be lower, so that the overtaking period would be 10.7 years. All the corresponding overtaking periods can be noticed in the table below.

| | Overtaking period for operational energy (Athens) | Overtaking period for operational energy (Riyadh) |
|---|---|---|
| TYPICAL CASE SCENARIO | 8 years | 10.7 years |
| CASE SCENARIO 1<br>Wall material change | 8 years | 10.9 years |
| CASE SCENARIO 2<br>Insulation material change | 7.4 years | 9.7 years |
| CASE SCENARIO 3<br>Floor material change | 8.5 years | 11.2 years |
| CASE SCENARIO 4<br>Window frame material change | 9 years | 11.7 years |
| CASE SCENARIO 5<br>Insulation doubling | 9.2 years | 12.4 years |

Table 2. Showing the period that operational energy needs in order to overtake the embodied energy (for both Athens and Riyadh)

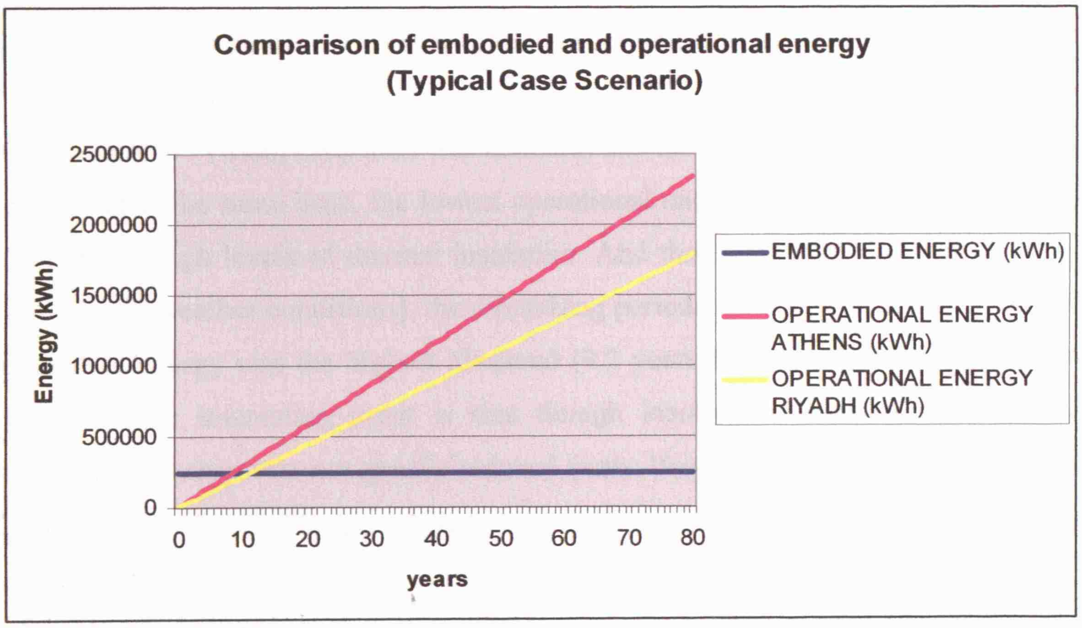



Figure 1. Showing embodied and operational energy throughout the years, for the typical case scenario.

If we consider the sum of embodied energy and operational energy as the total energy used in the building (for assumed lifespan of 60 years), then it can be concluded that the more the embodied energy increases, the more time it takes for the operational energy to overtake it. This can also mean that the embodied energy becomes increasingly important.

Throughout the five case scenarios, the materials were changed and the embodied energy had also been changing accordingly. This is not the case with the operational energy. It can be observed that in both cases (Athens and Riyadh) the operational energy underwent through tiny, insignificant changes, the highest one being 1.4% increase (compared to the typical case study). This means that indeed, embodied energy should be given more attention, as far as the construction materials of a building are concerned.

According to table 1, the embodied energy in the typical case scenario was 239,140 kWh. When the materials changed, (scenarios 1,2,3,4) especially in the case of insulation change, the total embodied energy was increased. In the same cases, the operational energy stayed in the same levels. This fact proves that the fluctuations in embodied energy do not necessarily affect the operational energy.

Case scenario 5 (when insulation was doubled) had the highest embodied energy of all cases, but at the same time, the lowest operational energy. It was a case of doubling the already high levels of thermal insulation. And that is why in both cases (Athens and Riyadh weather conditions), the overtaking periods for operational energy against embodied energy was the highest observed (9.2 years for Athens and 12.4 years for Riyadh). The interesting point is that though insulation thickness was doubled, operational energy was not greatly reduced (only 1%). Thus, it can be concluded the levels of insulation in the typical case study scenario were already sufficient.

The following chapter will include all the conclusions made in this study, concerning the embodied and operational energy individually, as well as collectively.

# Chapter 7. Conclusions

## 7.1 Conclusions

This study's aim was to understand the importance of the embodied energy of construction materials in an 'environmentally considerate' designed house in Athens. The comparison of this energy to the operational energy of the building was a further step in a clearer understanding of embodied energy.

As a general conclusion it can be said that embodied energy comprises a useful tool for the understanding of environmental impacts of a material or a product. Though, it should always be kept in mind that energy in use and the attempt to reduce it will always be far more significant.

Another useful point is that there has been a worldwide attempt to make buildings less energy consuming (in terms of energy in use). Since buildings are becoming less energy demanding, the operational energy will be decreasing, so that the embodied energy will be acquiring a higher significance.

In all five case scenarios (compared to the typical case) the operational energy did not go through any meaningful changes. Thus, the change of the materials that were tried did not play a significant role in the overall operational energy.

Since the doubling of insulation gave a 10% increase to the embodied energy, but not a very important one in the operational energy, it can be concluded that the 150 mm on external walls and 200 mm of insulation on the roof was proven to be enough for the specific building. As a general rule, it can be said that insulation thicknesses that are specified today in Greece are not sufficient.

When possible, glass wool insulation should be preferred (against extruded polystyrene), since it has a much lower embodied energy value.

Though marble is a local material, it is always better to prefer timber flooring, since it does not make a difference to the operational energy, but it does raise the total embodied energy of the building.

Timber framed windows should ideally be used in Greece, against aluminum ones. Again, they contribute a lower value to the total embodied energy.

As a general conclusion it can be said that the building was proven to work more sufficiently on a hotter and drier climate, rather than in the current climatic conditions of Athens.

As it has already been mentioned in a previous chapter, is that as the weather in Athens will become hotter, the cooling loads will significantly be increased. Furthermore, in the current weather conditions in Athens, the largest part of the annual energy in use is consumed for the heating of the house. And this can be an interesting point for the architects, engineers and other specifiers: in Greece they should focus their design more towards shading and cooling the house properly, rather than investing in great heating solutions. These will not be of a great use in a few decades from now.

Finally, as the climate will be becoming hotter, the house will be performing better.

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# Appendix 1

**Source**: ArchiCAD drawing, House in Aghia Paraskevi, Athens designed by Maria Ghiata and Kiki Kelesidou [September 2005]

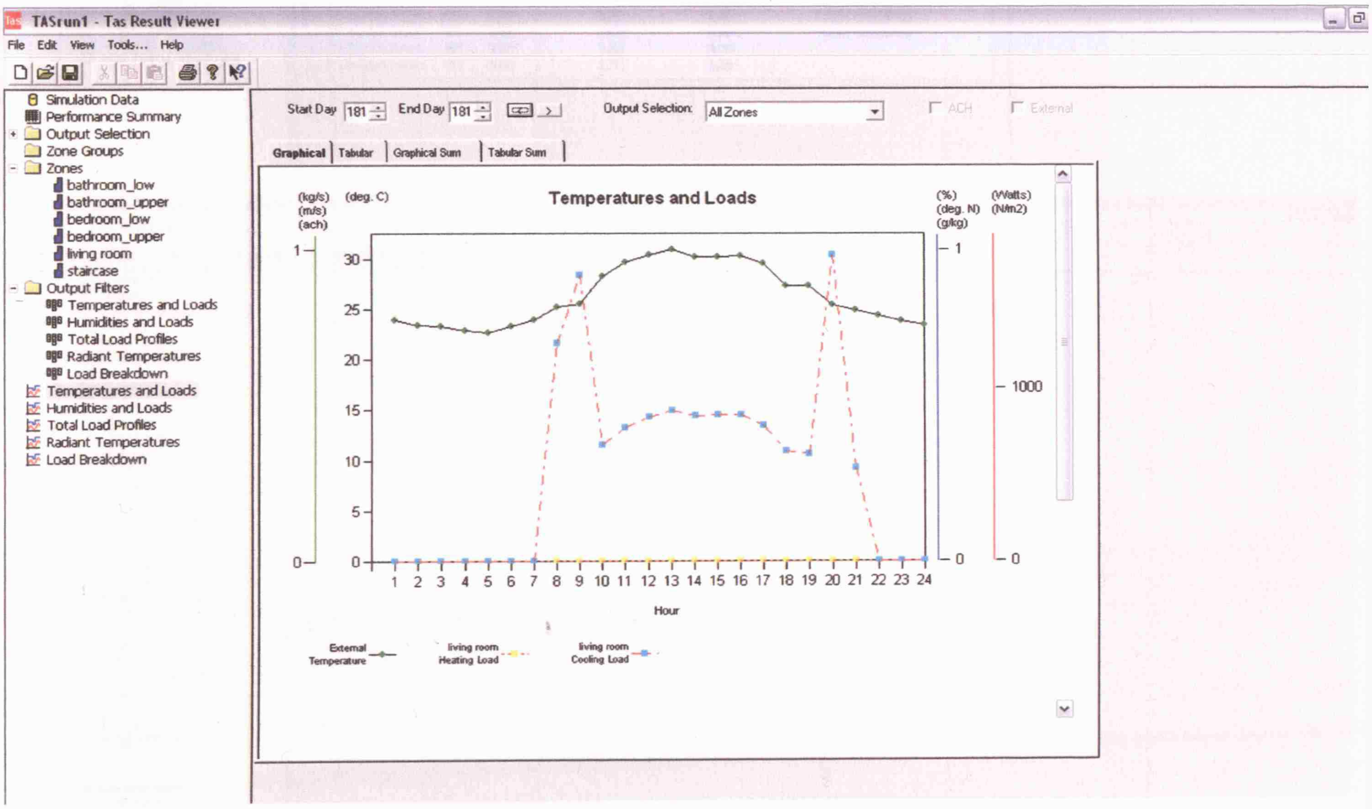
GROUND FLOOR PLAN
SCALE: 1/100

**Source**: ArchiCAD drawing, House in Aghia Paraskevi, Athens designed by Maria Ghiata and Kiki Kelesidou [September 2005]

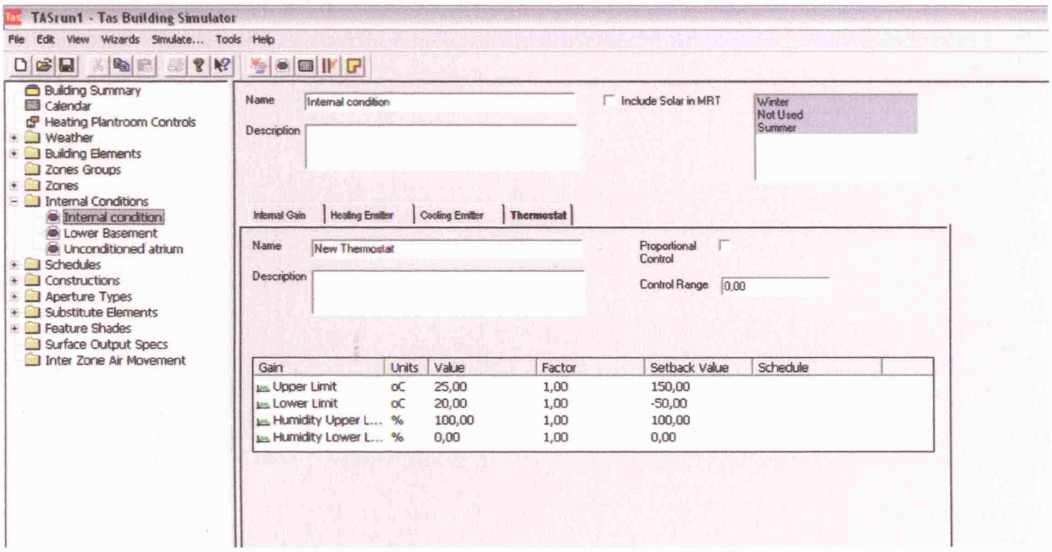
**Source**: ArchiCAD drawing, House in  Aghia Paraskevi, Athens designed by Maria Ghiata and Kiki Kelesidou [September 2005]

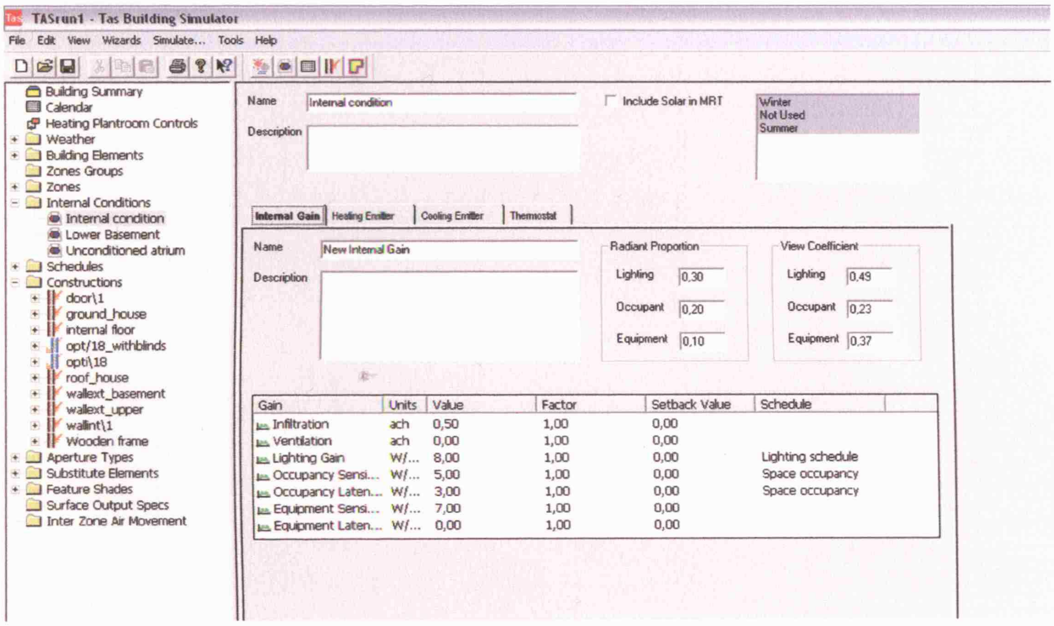
**Source**: ArchiCAD drawing, House in Aghia Paraskevi, Athens designed by Maria Ghiata and Kiki Kelesidou [September 2005]

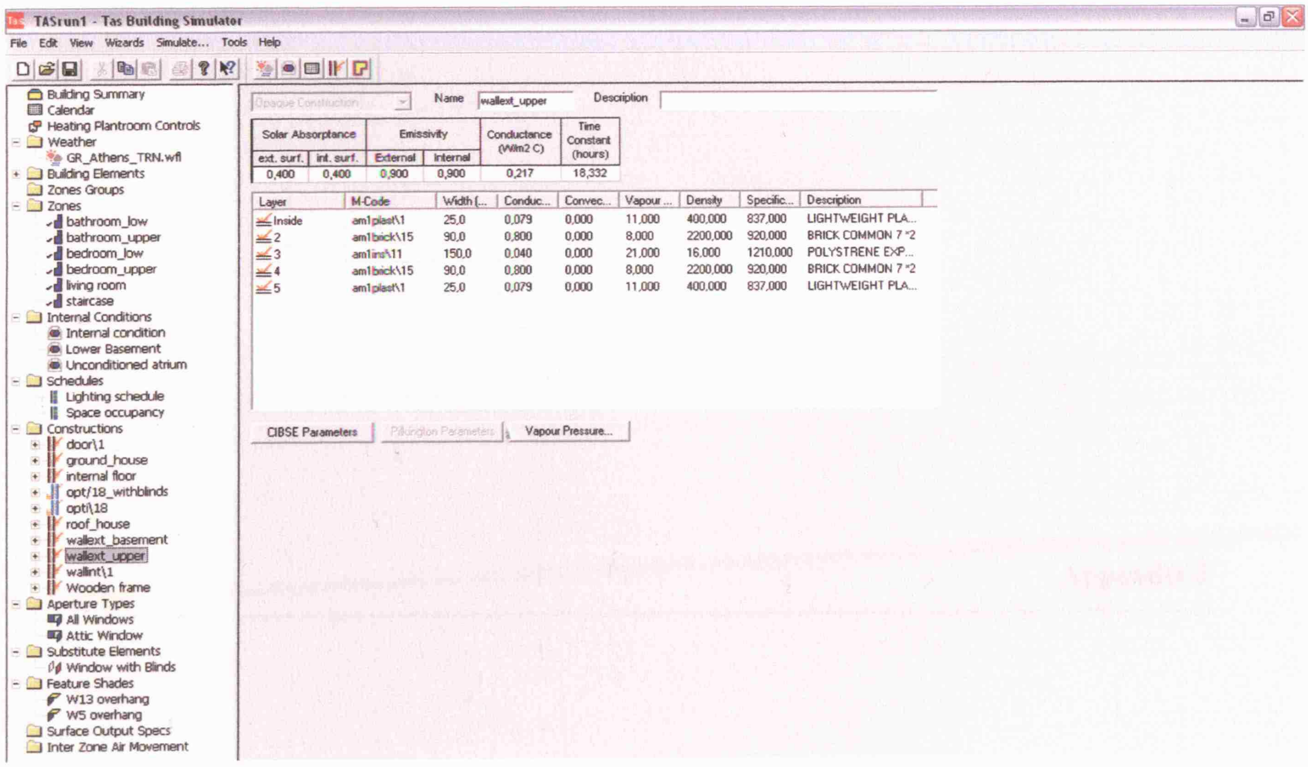
Appendix 2


A print from the results of the TAS program.
Two randon days were chosen: one representing the winter winter and one the summer period


TASrun1 - Tas Building Simulator
File Edit View Wizards Simulate... Tools Help
Building Summary
Calendar
Heating Plantroom Controls
Weather
Building Elements
Zones Groups
Zones
Internal Conditions
Internal condition
Lower Basement
Unconditioned atrium
Schedules
Constructions
Aperture Types
Substitute Elements
Feature Shades
Surface Output Specs
Inter Zone Air Movement
Name Internal condition
Include Solar in MRT
Winter
Not Used
Summer
Description
Internal Gain
Heating Emitter
Cooling Emitter
Thermostat
Name New Thermostat
Proportional Control
Description
Control Range 0,00
Gain Units Value Factor Setback Value Schedule
Upper Limit oC 25,00 1,00 150,00
Lower Limit oC 20,00 1,00 -50,00
Humidity Upper L... % 100,00 1,00 100,00
Humidity Lower L... % 0,00 1,00 0,00


TASrun1 - Tas Building Simulator
File Edit View Wizards Simulate... Tools Help
Building Summary
Calendar
Heating Plantroom Controls
Weather
Building Elements
Zones Groups
Zones
Internal Conditions
Internal condition
Lower Basement
Unconditioned atrium
Schedules
Constructions
door\1
ground_house
internal floor
opt/18_withblinds
opti\18
roof_house
wallext_basement
wallext_upper
wallnt\1
Wooden frame
Aperture Types
Substitute Elements
Feature Shades
Surface Output Specs
Inter Zone Air Movement
Name Internal condition
Include Solar in MRT
Winter
Not Used
Summer
Description
Internal Gain
Heating Emitter
Cooling Emitter
Thermostat
Name New Internal Gain
Description
Radiant Proportion
Lighting 0,30
Occupant 0,20
Equipment 0,10
View Coefficient
Lighting 0,49
Occupant 0,23
Equipment 0,37
Gain Units Value Factor Setback Value Schedule
Infiltration ach 0,50 1,00 0,00
Ventilation ach 0,00 1,00 0,00
Lighting Gain W/... 8,00 1,00 0,00 Lighting schedule
Occupancy Sensi... W/... 5,00 1,00 0,00 Space occupancy
Occupancy Laten... W/... 3,00 1,00 0,00 Space occupancy
Equipment Sensi... W/... 7,00 1,00 0,00
Equipment Laten... W/... 0,00 1,00 0,00


TASrun1 - Tas Building Simulator
File Edit View Wizards Simulate... Tools Help
Building Summary
Calendar
Heating Plantroom Controls
Weather
GR_Athens_TRN.wfl
Building Elements
Zones Groups
Zones
bathroom_low
bathroom_upper
bedroom_low
bedroom_upper
living room
staircase
Internal Conditions
Internal condition
Lower Basement
Unconditioned atrium
Schedules
Lighting schedule
Space occupancy
Constructions
door\1
ground_house
internal floor
opt/18_withblinds
opti\18
roof_house
wallext_basement
wallext_upper
wallnt\1
Wooden frame
Aperture Types
All Windows
Attic Window
Substitute Elements
Window with Blinds
Feature Shades
W13 overhang
W5 overhang
Surface Output Specs
Inter Zone Air Movement
Opaque Construction
Name wallext_upper
Description
Solar Absorptance
ext. surf. 0,400
int. surf. 0,400
Emissivity
External 0,900
Internal 0,900
Conductance (W/m2 C) 0,217
Time Constant (hours) 18,332
Layer M-Code Width (... Conduc... Convec... Vapour ... Density Specific... Description
Inside am1plast\1 25,0 0,079 0,000 11,000 400,000 837,000 LIGHTWEIGHT PLA...
2 am1brick\15 90,0 0,800 0,000 8,000 2200,000 920,000 BRICK COMMON 7 *2
3 am1ins\11 150,0 0,040 0,000 21,000 16,000 1210,000 POLYSTRENE EXP...
4 am1brick\15 90,0 0,800 0,000 8,000 2200,000 920,000 BRICK COMMON 7 *2
5 am1plast\1 25,0 0,079 0,000 11,000 400,000 837,000 LIGHTWEIGHT PLA...
CIBSE Parameters
Pilkington Parameters
Vapour Pressure...

# Appendix 3

BRE does not allow all the data for the environmental profiles of materials to be published. Thus a collection of other research groups in Europe as well as the rest of the world has been introduced and can be seen in the tables below.

| material | Danish Building Research Institute (Denmark) | Construction Industry Research and Information Association (UK) | Boostra &Knappen (Netherlands) |
|---|---|---|---|
| concrete | 11 | - | 17 |
| brick | 60 | 76 | - |
| steel | 834 | - | 473 |
| glass | 528 | - | - |

*Functional unit:* ***kWh/tonne***

| material | ATLA (New Zealand) | | Cole & Kernan (Canada) | | CSIRO (Australia) |
|---|---|---|---|---|---|
| | MJ/kgr | MJ/m3 | MJ/kgr | MJ/m3 | MJ/kgr |
| aluminum | 191 | 515,700 | 8.1** | 37,210 | 170 |
| brick | 2.5 | 5,170 | 2.5 | 5,170 | 2.5 |
| concrete | 1.0* | 2,350 | 1.3*** | 3,180 | 1.9 (in situ) |
| steel | 32 | 251,200 | 32 | 251,200 | 38 |
| local stone | 0.8 | 1,890 | 0.79 | 2,030 | 5.9 (granite) |
| plaster | 4.5 | 6,460 | 6.1**** | 5,890 | 2.9 |
| glass | 15.9 | 40,060 | 15.9 | 37,550 | 12.7 |
| extruded polystyrene | 117 | 2,340 | 117 | 3,770 | - |
| *Functional unit:* ***MJ/kgr*** ***or*** ***MJ/m3*** | | | | | |

* = concrete in 17.5 MPa (C1215 type)
** = recycled aluminum
*** = concrete in 30 MPa (C2025 type)
**** = plasterboard
1kWh/tonne = 3.6 MJ/ tonne = 3.6 MJ/ 1000 kgr = 0/0036 MJ/kgr